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Forest and Range
Experiment Station**

Fort Collins,
Colorado 80526

**General Technical
Report RM-161**

The 1988 Symposium on Systems Analysis in Forest Resources

March 29 to April 1, 1988

Asilomar Conference Center
Pacific Grove, California



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Preface

In 1975, the Society of American Foresters' Systems Analysis Working Group sponsored a Working Group Symposium on Systems Analysis in Forest Resources Management. This meeting was held in Athens, George at the University of Georgia. In 1985, after a hiatus of 10 years, a second symposium was held at the same location. During this meeting, it was agreed to start holding those meetings every three years.

These proceedings contain the papers of the third such symposium, held in Asilomar, California in the spring of 1988. As with the first two meetings, a diverse and interesting group of papers was presented. General topic areas include land management planning, artificial intelligence, multicriteria optimization and fuzzy systems, regional timber supply analyses, stand level optimizations, and timber harvest scheduling.

In this publication, papers are arranged in sections corresponding to the sessions of the symposium. Papers presented in the poster session appear at the end.

We thank the keynote speakers, Mr. Jeff M. Sirmon and Mr. Robert Ewing, and to Dr. Stuart E. Dreyfus and Dr. Michael H. Rothkopf who presented excellent tutorials on artificial neural networks and oral vesus sealed bidding systems for selling resources.

As always, the participants are the heart of this type of meeting. We thank them for their involvement, and for submitting their papers in electronic form to help speed publication. The opinions expressed in these proceedings are the authors' own, and do not necessarily reflect those of the USDA Forest Service or the other sponsoring organizations.

Finally, thanks are also due the sponsors for their support.

We look forward to the next meeting, now scheduled for 1991.

Brian M. Kent
Larry S. Davis

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USDA Forest Service
General Technical Report RM-161

June 1988

The 1988 Symposium on Systems Analysis in Forest Resources

March 29 to April 1, 1988

**Asilomar Conference Center
Pacific Grove, California**

**Brian M. Kent and Larry S. Davis
technical coordinators**

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Integrated Planning as Negotiation: A California Perspective on Forest Planning Analysis Requirements

Robert A. Ewing[1]

Abstract.--Forest planning in California is challenged by a dynamic social environment. In response, California Department of Forestry and Fire Protection and the University of California, Berkeley, have initiated a project to better coordinate federal-state forest planning. The project is based on the concept of planning as negotiation. This involves a focus on collaborative approaches to resolving policy disputes, development of options for mutual gain, and identification of strategies for institutional adjustment. The primary use of systems analysis is to provide a quantitative representation of options for mutual gain.

Forest planning in California is a complex enterprise involving a variety of agencies, levels of government, and interest groups. Since 1974, the USDA Forest Service has been attempting to implement its responsibilities under the Forest and Rangeland Renewable Resources Planning Act and the National Forest Management Act (NFMA) relative to national, state, and local needs. To date, the agency has published several national assessment and program documents that bear, to some degree, on management issues in California. A guide for the Pacific Southwest Region has been published, and each of California's 18 national forests has published a plan that is either final or in some stage of final review. On the state side, the California Department of Forestry and Fire Protection has been mandated to produce a periodic forest and rangeland assessment and to work with the California Board of Forestry to write an accompanying policy statement. These two reports currently are being completed.

Attempts have been made to coordinate these various planning and assessment efforts, but they have been only marginally successful. Effective integration of planning programs in California is more a goal than a reality.

This said, the Department of Forestry and Fire Protection's Forest and Rangeland Resources Assessment Program (FRRAP), in cooperation with the University of California, Berkeley, is attempting to develop a process to better coordinate federal-state forest planning. The Washington and Regional offices of the Forest Service have been invited to join the project.

This paper presents the broad outlines of this process. My purpose is threefold. First, I would like to provide some feel for the contemporary dimensions of forest planning in California. Second, I want to introduce the concept of planning as negotiation. Third, I will attempt to define some general requirements for systems analysis given an integrative approach to planning.

For lack of better term, I will define our approach to planning and systems analysis as a process of large-scale, multi-party negotiation. The goal of planning as negotiation is: (1) to define a collaborative approach for resolving forest policy disputes; (2) to identify planning results that produce benefits for mutual gain; (3) to recommend necessary institutional adjustments; and (4) to create the analytical infrastructure to support all this.

While both Forest Service and state planning are at least ostensively directed to such goals, the record of accomplishment is not good. In addition, the development of operations research tools generally has not been thought of in these terms. The point of this paper is to suggest that there is a need to design a planning and analysis process that produces negotiated agreements on the future direction of forestry, at least in California.

Dimensions of Planning in California

The need for a new approach to forest planning in this state stems from the dynamic environment that forest planners face here. For various reasons, the progress made in completing

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California national forest plans is behind most other regions. Our work in FRRAP also has taken a greater investment in time and effort than originally anticipated. The scope of the planning problem, the changing importance of the resource base and its uses, and the wide variety of groups concerned with resource policy require a substantial, sophisticated, and anticipatory approach to planning. We are only now beginning to come to grips with these realities.

While change occurs in all parts of the U.S., the California experience is unusual. For more than a century, California has experienced a population explosion of unparalleled proportion (Bradshaw 1986). In the years since statehood, the number of Californians has doubled on average every 20 years. This represents the fastest long-term population growth of any industrialized region in the world. In 1900, there were 2 million Californians. Today, there are nearly 27 million. Since 1957, when we passed New York, California has been the most populous state in the nation.

This breakneck pace is not projected to continue. The population is not expected to double again until after 2050. Still, population growth and ethnic diversification will remain a dominant force for change. Projections for the year 2000 indicate a population of 31 million, and by 2020, 37 million (California Department of Finance 1986). Thus, in the next 12 years, we will add 4 million people, or more than currently live in the city of Los Angeles.

California's population growth has been accompanied by an equally robust economic explosion. The State's economy is currently one of the most powerful in the world, producing nearly $500 billion of goods and services annually (Wells Fargo Bank 1986). This ranks California sixth among the world's economies. The State's economic growth is characterized by what economists term advanced industrial development. This means that the economy has become dominated by rapid advancements in communications and transportation technology, growth in service sector firms and jobs, and a relative decline in the importance of primary resource industries.

Two groups of basic industries, high technology and diversified manufacturing, are accounting for 90 percent of the industrial job growth in this decade. California will account for fully 30 percent of all high technology jobs created nationally during the 1980's (Center for the Continuing Study of the California Economy 1982). In sum, this state is among the leaders of an important industrial transformation that has global significance.

The implications of this transformation for resource management and forest planning are multifold. First, of course, there are tremendous new requirements for resource goods like timber, recreation, water, and open space. Ironically, however, while California represents one of the top three producers and the top consumer of wood products in the nation, the demand for timber is being outstripped by demands for other goods and services. In a very real sense, our economic strength frees us, at least to a degree, to depend on wood products imported from other areas. But relatively fixed goods like recreation opportunity, water, and wildlife habitat are becoming more scarce, and, therefore, more important to California consumers.

Such change in the relative value of forest-based goods must be better incorporated into our planning models. More significantly, planners need to promote institutions to capture the economic value of these so-called noncommodity goods to fund the management costs of producing them (Binkley 1987, O'Toole 1988).

Second, although the majority of California's growth is around cities, rural areas are also experiencing increases in population. In fact, 10 of the 15 fastest growing counties, in relative terms, are in rural forest and rangeland areas (California Department of Forestry and Fire Protection 1988). The implications of this rural migration are many, including higher land values, landownership fragmentation, checkerboard patterns of alternative uses, and increased political conflict over traditional management activity.

From the standpoint of forest planning, one of the most compelling aspects of exurbanization is the need to evaluate the cumulative effects of development and management under dynamic conditions. As more people move into the woods, we must find ways to anticipate the environmental and economic consequences. This involves the capacity to look beyond the boundaries of an individual planning unit such as a national forest, to review behavior in a mixed ownership context, and to design adequate systems of mitigation.

Third, California's social and economic transformation has a strongly urban flavor. Cities, indeed megacities, are the center of action for high technology growth. Thus, while patterns of exurbanization are developing, more than 90 percent of our citizens live in cities and this proportion is expected to hold over time. City populations dominate our political landscape and this generally translates into an environmentally-oriented focus. A 1984 California poll (Field Institute 1985) indicated the dominance of an environmentalist perspective among Californians. The poll found that 27 percent of the population considers themselves to be environmentalists. Sixth-two percent believe they are somewhat environmentally oriented. Only 10 percent hold no environmental leanings at all. In response to a question on the need to balance growth with development, 27 percent favored slowed growth, 65 percent want a balance, and only 5 percent would like to see environmental protection relaxed to promote growth. These percentages hold steady across political affiliation, age, and other characteristics. Only place of residence, urban versus rural, makes a difference. Rural residents, on average, would like to see more growth. Additionally, the California poll was replicated quite well by the vote in November 1986 on Proposition 65, a so-called clean water initiative.

Strong environmental sensitivities have several political and planning effects. First, there is general support for large-scale environmental projects. The 1984 California Wilderness Bill, which added more than 2 million acres of wilderness in the state, is one such example. Another is the establishment and expansion of Redwood National Park. Current proposals include several new national parks in the desert and along the Smith River in

Northern California. Such large-scale events cannot be ignored by planners. One of the primary reasons our national forest plans are behind schedule is the difficulty the Forest Service has had adjusting to the wilderness bill. The spotted owl issue can be viewed as a similar phenomenon.

The urban dynamic in environmental politics also means tremendous political competition over forest planning. Interest and environmental groups adopt various strategies to influence planning. Politicians make careers over support or opposition to resource decisions. Currently, although the Department of Forestry and Fire Protection has been designated a lead role in commenting on national forest plans, other departments in state government and the State Attorney General have made contrary and contradictory sets of comments.

This intense political competition over resource decision making has to be addressed by planners. And because of the competition, additional statutory help to ensure improved coordination or to further rationalize planning is not likely to be forthcoming. Planners must take the initiative on their own to coordinate diverse interests and energies towards a common purpose. Legislatures will not do this for them.

Planning as Negotiation

One approach to reaching a consensus on goals and means is a system of planning as negotiation. As mentioned, we are currently attempting to develop such a process in California. There are at least eight characteristics to this type of planning (table 1). These can be described briefly as follows:

1. Planning as negotiation deals with broad-scale social, economic, and political trends affecting forestland use and management. As I have tried to demonstrate, various social patterns beyond the land base are having a substantial effect on California forestry. Such patterns cannot be ignored by planners. We must develop more sophisticated approaches to modeling alternative scenarios that represent the resource-related implications of dynamic demographic, social, and political trends.

   Importantly, significant efficiencies can be gained through collaborative development of common data bases and analytical tools in this area. There is no reason for each national forest or for Forest Service Regional office and the state to develop separate sets of projections. We can all benefit from cooperation in trend assessment activities.

2. Following suggestions by Irland (1986), planning needs to recognize that goals are not fixed, but variable. In fact, one of the primary purposes of our project is to open up the debate about the goals of forestry and to recognize their dynamic nature. One of the primary purposes of planning, and one of the best tools planners have, is to force people to think strategically about the future.

3. A corollary proposition is that negotiation focuses on interests and not on issues. Issues can be sexy and draw public attention, but interests represent more fundamental, and perhaps more flexible, perspectives on the value of forests. Focusing on interests rather than positions can work for two reasons. First, for every interest there usually exist several possible positions that can satisfy it. When you look behind opposed positions for motivating interests, alternative positions that meet the interests of several groups can often be found. Second, reconciling interests rather than compromising on issues works because behind opposed positions lie many more interests than the conflicting ones (Fisher and Ury 1983).

Table 1.--Characteristics of planning as negotiation.

1.	Deals with broad social, political, and economic trends.
2.	Deals with situation in which goals are not fixed, but variable.
3.	Focuses on interests, not positions.
4.	Deals with multiple ownerships, agencies, and interests.
5.	Invites all parties to the table.
6.	Insists on using objective criteria.
7.	Creates options for mutual gain.
8.	Treats institutions as real, not assumed.

[1]*Adapted from Irland (1986) and Fisher and Ury (1983).*

4. Successful negotiation depends on the involvement of all parties with some stake in forestland and resource use. There are obviously multiple parties concerned with forestry's future in California and they need to be included at each phase of the planning process. A recent study of public involvement in commenting on the Tahoe National Forest draft plan demonstrates the alienating and polarizing effects of running public involvement as a beauty contest (Fortmann and Lewis 1987a).

   Essentially, three objectives should direct public involvement in planning:

   a. to elicit participation from a representative as a sample of the public and other agencies as possible;

   b. to elicit participation in a process that provides the participants with the same information as the agency and that adequately and accurately reflects their knowledge and concerns; and

   c. to generate commitment to a final decision perceived by all parties as legitimate (Fortmann and Lewis 1987b).

6. Negotiated planning insists on the use of objective criteria. One of the important tenets of professional forestry has been the utility of rational decision making. FORPLAN (Johnson 1986), CALPLAN (California Department of Forestry and Fire Protection 1988, Davis et al. 1985), and other models represent important systems for quantifying and objectifying resource decision making. Unfortunately, as discussed below, they have not been linked sufficiently well to the actual decision making process. Yet, the more we bring standards of fairness, efficiency, or scientific merit to bear

on a problem the more likely are we to produce a solution that is wise and broadly accepted.

7. Planning as negotiation focuses on the development of options for mutual gain. Planning too often is seen as an analytical rather than a creative process. But what is most needed in forestry is a wide-ranging exercise in invention. We must learn to try to invent the future, if we are to have an important role in it.

   Too often, forest planning assumes a goal of allocating fixed resources under conditions of scarcity. While there is truth to this analogy, it generally forces us into a debate over how to divide up a fixed pie. Instead, we need to be more creative at broadening the options on the table. While the notion of mutual gain has a decidedly Pollyannese ring to it, we have hardly uncovered all the ways forests can be used, managed, administered, and protected. A major goal of planning has to be the development of new options for land use and management, and most importantly, of new options for administration and planning.

8. This latter point raises the issue that the institutional environment cannot be assumed as given. Forest planning and allocation theory cannot continue to assume away the need for, or the opportunities of, institutional adjustment. In many cases, the surest way of exploding the limits of a fixed pie is to open up an analysis problem to include new institutional alternatives. Examples might include looking at several national forests in combination, at a mixed ownership situation, or at the opportunities to change the way resources such as wilderness or water are administered.

One positive contribution, the so-called new resource economists have made to forestry discourse, is to challenge several of our institutional assumptions (O'Toole 1988, Stroup and Baden 1983). While "market solutions" hardly hold all the answers, proposals for wilderness endowment boards, public cooperations to manage national forest timber, and new fee arrangements for recreation do open our eyes to new approaches. To date, the idea of altering the institutional structure of forestry has been largely the purview of those outside the forestry profession. But, such ideas are the essence of forest planning as negotiation.

Analysis Requirements for Planning as Negotiation

Even with this cursory view of planning as negotiation, some technical support requirements spring to mind. Davis (1988), in an accompanying paper, describes a decision support information system suitable for multiple-party negotiation on forest planning. I will simply develop several themes for consideration.

A first point is to recognize that the primary use of system analysis in planning as negotiation is to provide a quantitative representation of options for mutual gain. Consequently, models that allow simulation of alternative scenarios rather than an optimal solution of a fixed planning problem are most appropriate. In practice, optimization techniques may have considerable value as information generation tools. But a premium is placed on the development of an analytical capacity to simulate the effects of large-scale social trends--and of policy options--on land condition, management strategy, and economic, social, and political conditions.

Such analysis systems need to be large-scale, flexible, and relatively generic to be useful. As an example, FRRAP has been working towards the development of a simulation model and data base to represent all forest and rangeland ownerships in California. CALPLAN (California Department of Forestry and Fire Protection 1988, Davis et al. 1985) allows for the representation of the effects of changing demands and demographic patterns on the behavior of all public and private landowners, by region of the state and vegetation type. It is flexible in that any combination of ownership, vegetation type or condition, geographic location, or forest output can be addressed. Thus, we can look at several national forests in combination, at a mix of public and private owners in a given water basin, or at all forestlands in an economic region.

Such capacity is required to address many forest policy issues that arise in California and is a analytical prerequisite for generating options for mutual gain. It is not enough to model the tradeoffs among different combinations of forest uses (Connaughton and Fight 1984), one must also represent how various trends affect those levels of use and how a combination of policy options can result in different social and economic outcomes. In addition, plan alternatives must incorporate the political and institutional changes required to bring them about.

To such an end, planning as negotiation requires analytical procedures that are accessible and understandable to the participants and affected interests of forest planning. Binkley (1987) has noted the ways in which the use for FORPLAN has excluded important people from the national forest planning process. From a negotiation perspective, the process of analysis only makes sense if it allows interests to sit down and "make deals" to arrange contracts for transferring resources, to link plans, and to vary the institutional environment in order to achieve mutually beneficial goals (Davis 1988). In other words, planning as negotiation requires us to develop models that decision makers can understand and use as they engage in negotiation. Such models must allow planning participants an opportunity to incorporate their own knowledge and information into the process, to keep score as negotiations proceed, and to invent options for mutual benefit.

Benefits and Consequences

Various authors have noted that the legislative planning statutes of the 1970s have not resolved all conflict over forestry, nor made it possible to meet all demands on forestlands (Behan 1979, Dana and Fairfax 1980). Planners in California find these observations to be compelling. We exist in a dynamic social environment that provides much uncertainty and scant opportu-

nity for consensus on issues. Nevertheless, strategic planning procedures and options can be developed to gain greater influence over the future.

One such approach would be a collaborate approach to forest planning perhaps involving the Forest Service, University of California, Berkeley, and California Department of Forestry and Fire Protection. Based on a model of planning as negotiation, this project would attempt to chart a new course for planning in California. It would put planners in something of a new role. Rather than focusing on analytical systems that met the bottomline of statutory direction, an effort would be made to actually address the problems we face. This process does not place planners above democratic procedures, rather, it forces us to use them. The goal is to discover new ways to use, manage, administer, and protect the state's forests, so they can play a relevant role in California's future.

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Definition of the Integrated Federal-State Planning Problem

Lawrence S. Davis[1]

Abstract--Integrated Federal-State planning (IFSP) requires joint and simultaneous consideration of planning and policy options on all Federal, State, and private lands within the State. Virtually all analysis of related problems is limited to single decision maker, multiobjective programming (MOP) techniques, primarily goal programming. The IFSP problem differs in two important respects: it is a multi-decision maker, multiobjective problem, and it considers multiple landowners within a common problem formulation. Analysis of the IFSP problem is directed to providing information about feasible aggregate choices and educating and facilitating negotiation by the multiple decision makers involved in the problem. California is used as a case study to illustrate the definition of the problem. Initial results show the strong aggregate tradeoffs at the State level between retention area and/or budget vs. timber, forage, water, and developed recreation.

The Integrated Federal State Planning (IFSP) problem is defined in the context of a State's concern with independent planning by federal, state and private landowners within its political borders. States, particularly the Western states, want to evaluate and comment on the aggregate and cumulative effects of proposed changes in the management plans of one ownership sector, such as the Forest Service, in terms of outputs from all ownership sectors. Increasingly, the states are contemplating policy and programs that enhance beneficial and will prevent or mitigate adverse collective effects of wildland planning. Such actions will politically involve all landowners and affected interests in the IFSP problem.

Assembling comparable, comprehensive information about all wildlands and all owners is difficult. Typically each federal agency, state agency and private organization keeps its own data base, has a different analytical system, and sets a different timetable for collecting data and planning. As a result information is not easily arrayed to portray and evaluate combined effects. Moreover few States have invested in obtaining and organizing the needed information and most are just now struggling to define their role in Federal-State planning.

Forest Service planning under RPA/NFMA is a significant agenda item in many States and is challenging their ability to work with the IFSP problem. Exacerbating the problem is the Forest Service's treatment of each forest as an independent planning unit. Draft plans for the forests within a State are released at different times over 10 to 20 months and the only effective option given the State is commenting on a plan-by-plan basis in order to meet the 90-day NEPA comment period constraint. This particularly impacts the Western States that need to process and evaluate up to 20 individual plans. What the State wants is for all plans to come out at about the same time and/or to have a year or more for comment after the last plan is released.

Several States are now making a serious effort to assemble the needed information and interact with the Forest Service at the State level of aggregation. Idaho requested a statewide analysis of the aggregate and cumulative impact of Forest Service plans on the State's economy and employment. Oregon, where timber supports some 50 percent of the State's economy, is mounting a comprehensive review directed from the Governor Goldschmidt's office to assess the combined impacts of projected Federal and private timber supplies on the Oregon timber economy and to develop a substantive State response to Forest Service plans. California is just finishing a comprehensive assessment of all private industrial and non-industrial forest and rangelands within the State to project production of timber, forage, wildlife habitat, water, and recreation. This information, when coupled with Forest Service DEIS data on the planning choices for 17 National Forests, presents a comprehensive

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picture of what the future may hold for California if all plans are implemented.

If any institution is going to coordinate the current independent planning of resources, it would have to be State government. Only the States have a clear and vital interest in the collective effects of land use within their boundaries. Moreover they are the political unit with enough clout to force serious evaluation and coordination of land use planning activities over multiple public and private ownerships. Integrated Federal-State planning is actually something of a misnomer; we are really talking about integrated planning of public and private lands under the presumably benevolent and enlightened direction of Federal and State governments. Private landowners and private interest groups are understandably suspect of public motives and will insist on full participation in any such process. Four developments are needed to make IFSP function: (1) a clear formulation and articulation of the State's interest and role in Federal Planning, (2) the existence of incentives for private landowners and affected interests to consider integrated planning, (3) development of a suitable decision support information system to evaluate and display aggregate choices and their consequences from many points of view, and (4) the design of an appropriate forum, participant list and negotiation procedure for integrated Federal-State planning.

The primary objective of this paper is to give a more formal definition of the Integrated Federal-State planning problem as a decision problem and to outline one scenario as to how an interactive, multi-decision maker negotiation process might approach its solution. A secondary objective is to suggest how a modified goal programming formulation might be a suitable framework to organize information to support the negotiation process. A quantification of the model for DEIS plan choices currently defined for California National Forests is presented as a case study and some initial results discussed.

Formulation of the IFSPP as a Decision Problem

This paper assumes that the Federal and State land agencies have decided that significant net social gains can be realized through coordinated planning and they agree to jointly work at effecting an integrated planning process. Analysis and decision making for the IFSP problem is assumed to have limits on time, budgets, and other planning resources. Moreover, like all planning, the goals of the participants and the aggregate constraints on the problem change with time. Hence this planning problem is characterized as a continuous problem for which discrete periodic decisions are made to allocate resources and implement activities and policies. Planning tries to capture this constantly evolving problem through a quantitative "snapshot" that is analyzed to help guide decision making, fully aware that by the time the decision is made the snapshot is out of date and a new one needed. Periodic decisions are administratively made by individual landowners in an open, politicized negotiation process involving governments, other landowners, and affected interests. In this broad outline, the process is about the same as that prescribed by regulation for National Forest planning. The important differences are twofold: the existence and recognition of multiple decision makers--active participants with different goals and agendas--and the explicit inclusion of multiple land ownerships in the formulation of a common problem.

Participants in the IFSPP

People representing Federal, State, and private landowners, Federal, State, County, and City governments, and major affected interest groups such as water users, recreationists, commodity, and environmental interests will want seats at the negotiating table. Each interest is treated as an independent decision maker with a different set of goals and different weights on the importance of outputs from the forests. Procedurally, selecting a workable number of participants to actively represent this broad spectrum of interests will be a major issue.

Let d_j represent decision maker j, j = 1...j

q_i represent forest output of type i, i= 1...i

Outputs and Activities

If each of the representative decision makers were interviewed and asked to state the relative importance of the different forest outputs and activities to their goals on a scale of, say, 0-9, we would expect their initial statements to provide a result such as illustrated in table 1. The weighting of decision makers such as d_1 or d_4 suggest they might be hired staff representatives of organized interest groups with narrowly defined interests, explaining the zero weights assigned to many outputs. Others, such as d_3 or d_4, might represent public agencies or government units who tend to take a comprehensive view and consider nearly all outputs to be of some importance.

A first order need of analysis is to identify which forest outputs and activities to quantify and track. This requires formalized interview and relative assessment, particularly with the multiple decision maker problem where the list of outputs of import to at least one person will be long.

Table 1.--Relative value of forest outputs to different decision makers measured on a 0-9 scale.

Forest Output q_i	Decision maker d_j			
	d_1	d_2	d_3	d_4
Timber harvest	9	5	4	0
Water yield	3	7	2	0
Acres old growth	0	2	1	9
Developed recreation	0	1	7	4
Forest jobs	0	5	6	0
Biological diversity	0	2	0	4

Decision Variables for Integrated Planning

Within the geographic boundaries of the State, forests and other wildlands are distributed over thousands of different private and many different public owners. Most of these ownerships are a single planning unit but some, such as the Forest Service or large industrial companies, are broken down into several individual planning units. For each planning unit, at a given point in time none, one, or more than one mutually exclusive plan has been developed and written for the management of the unit. A unit without a plan is being managed in some way, its just that a plan is not written or otherwise known and thus not currently available to the aggregate planners.

Let x_{lm} = plan l for planning unit m, l = 1...l, m = 1...m

and $\Sigma_l\ x_{lm} = 1.0$, for m = 1...m (plans are mutually exclusive)

Assume a State has four planning units. The list of unit plans available for consideration and analysis by our integrated state-level planners to consider might be as follows:

Unit 1, $\{x_{11}, x_{12}\}$ (Bureau of Land Management)

Unit 2, $\{x_{21}\}$ (Industrial Forest Lands)

Unit 3, $\{x_{31}, x_{32}, x_{33}, x_{34}, x_{35}\}$ (U.S. Forest Service)

Unit 4, {no data available} (Non-industrial forest lands)

Because each plan is a mutually exclusive choice for each planning unit, the complete set of aggregate choices available for State level consideration is all permutations of known mutually exclusive choices for the individual planning units.

Let S_k = aggregate choice k, k = 1...k

In our example no information is currently available on unit 4. Because of this, the aggregate State choices are initially quantified by plan choices from units 1, 2, and 3 with a blank for unit 4 (x_{4m}). Presumably an early order of business will be to obtain some information on unit 4. There are ten permutations in this example (2 x 1 x 5 = 10).

$S_1 = \{x_{11}, x_{21}, x_{31}, x_{4m}\}$

$S_2 = \{x_{11}, x_{21}, x_{32}, x_{4m}\}$

. . . .

. . . .

$S_{10} = \{x_{12}, x_{21}, x_{35}, x_{4m}\}$

To illustrate, a hypothetical data set for the unit plan choices (table 2) is aggregated to form State aggregate choices S_1 to S_{10} (table 3). Cost information is also included to calculate the budgets required by the various aggregate choices.

Two forest outputs are assumed to be of collective importance: volume of annual timber harvest (q_1), and forest acres reserved from timber harvest (q_2). When the set of 10 aggregate choices are mapped into decision space for this problem, we obtain a feasible region in terms of total state outputs (fig. 1). The

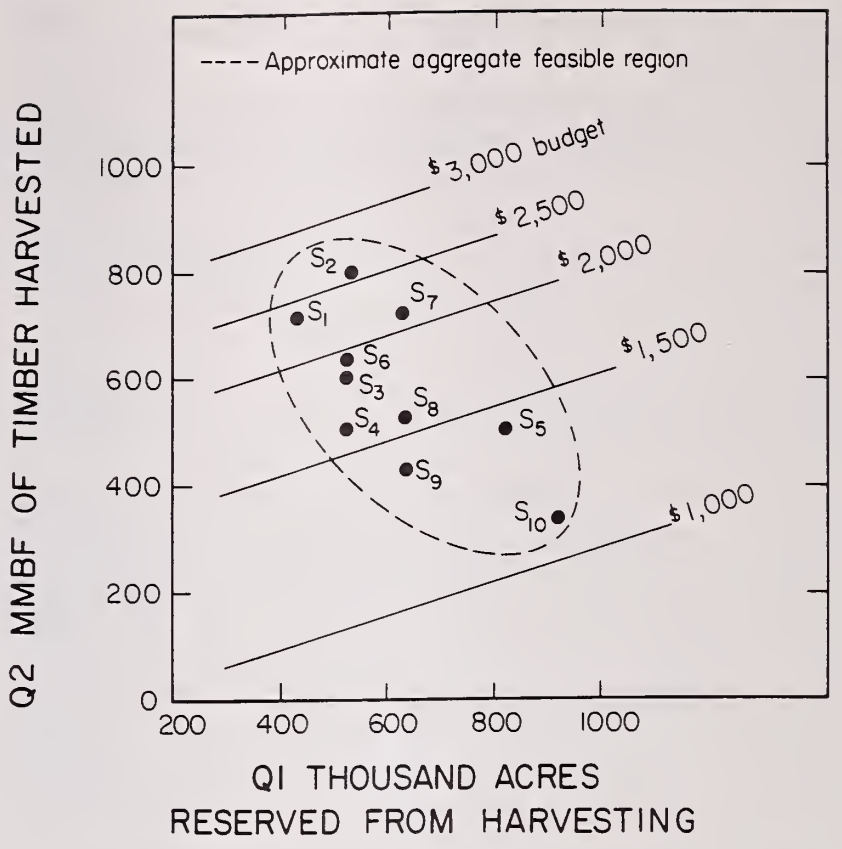


Figure 1.--Aggregate choice feasible region mapped in decision space.

feasible region is partitioned into subsets of choices that are available at budget levels of $1000, $1500, $2000, $2500 and $3000. The discrete aggregate choices are enclosed by the dashed line to suggest a contiguous feasible space that contains additional but as yet undefined choices. We cannot, however, use the convex combination of the existing solutions to form new choices. This is because many such combinations may not be feasible when traced back to the actual planning unit and the full range of spatial and other unique local constraints are imposed. Since the aggregate choice is made up of mutually exclusive,

Table 2.--Planning unit data for an integrated planning example.

Planning unit	Unit choice	Timber harvest *(MMBF)*	Area reserved *(M ACRES)*	Cost *(M$)*
BLM				
	X11	120	300	500
	X12	40	400	200
Forest industry				
	X21	200	10	600
Forest Service				
	X31	400	100	1000
	X32	500	200	1500
	X33	300	200	800
	X34	200	200	600
	X35	100	500	600
NIPF	X4M	--no data--		

Table 3.--Aggregate planning choices available to the state.

Aggregate choice	Planning unit elements	Timber harvest *(MMBF)*	Area reserved *(M acres)*	Aggregate cost *(M dollars)*
S1	X11 X21 X31	720	410	2100
S2	X11 X21 X32	820	510	2600
S3	X11 X21 X33	620	510	1900
S4	X11 X21 X34	520	510	1700
S5	X11 X21 X35	420	810	1500
S6	X12 X21 X31	640	510	1800
S7	X12 X21 X32	740	610	2300
S8	X12 X21 X33	540	610	1600
S9	X12 X21 X34	440	610	1400
S10	X12 X21 X35	340	910	1200

non-divisible unit plans, it follows that the aggregate choice itself is also mutually exclusive and non-divisible. At the very least, any new choice conceptualized as a linear combination of two or more existing aggregate choices needs to be disaggregated to the planning units and checked for feasibility prior to assuming the new aggregate is also feasible.

Evaluations of the Aggregate Feasible Set by Individual Decision Makers.

Two types of subjective approaches might be used by an individual decision maker to identify a preferred choice: (1) direct and (2) indirect. In the direct approach, the decision maker accesses his or her utility function and directly select a preferred solution from decision space. Figure 2 illustrates this: the initial feasible region of figure 1 is examined by decision maker number 1 using her utility function U_1 to choose point S_7. The second decision maker, with a different utility function U_2, selects point S_{10} from the same feasible region.

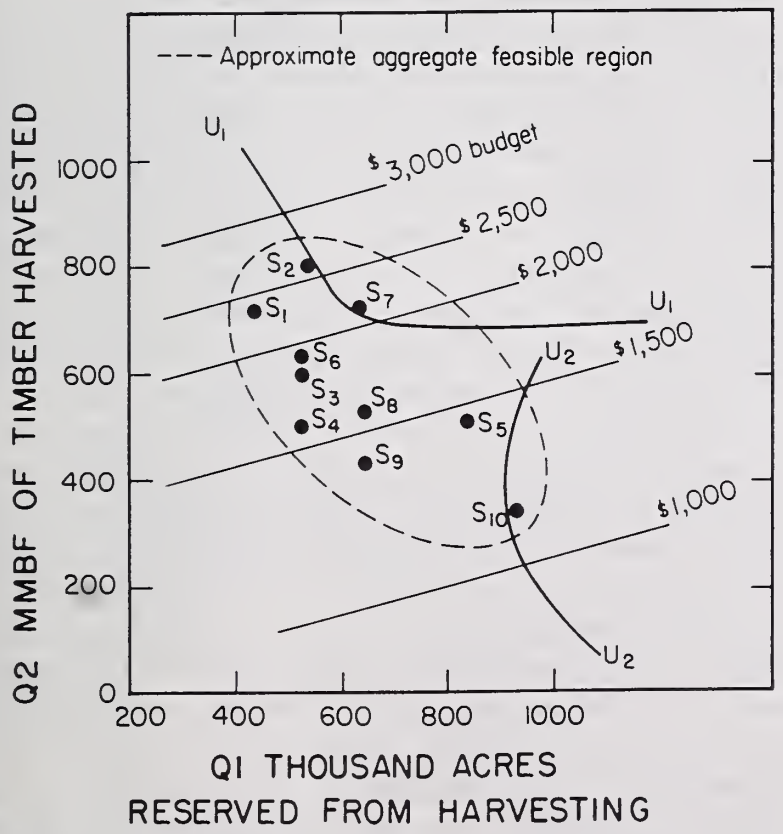


Figure 2.--Direct selection of aggregate choice from decision space.

In the indirect approach, the decision maker first attempts to articulate specific goals and then formulate an explicit objective function to calculate the goal value of each aggregate choice variable (S_k). These results are then used to map the feasible region from decision space into a feasible region in objective space. With this additional and more organized information, the decision maker's utility function is again used to make a final choice. To illustrate the indirect approach, considers two decision makers who each have the same two goals: income (Z_1), and aesthetic quality (Z_2). Where they differ is in their evaluation of how different outputs contribute to these goals. Table 4 shows how the two might assign relative weights to the outputs to form linear objective functions for each goal. The first decision maker

Table 4.-- Objective criterion coefficients used by two decision makers for calculating achievement of their income and amenity goals.

	Decision maker #1		Decision maker #2	
Forest output	Income goal	Amenity goal	Income goal	Amenity goal
Q1 Timber harvest	8.0	3.0	4.0	1.0
Q2 Reserved area	0.0	4.0	2.0	10.0

obtains about as much aesthetic pleasure from viewing the managed forest as she does from viewing uncut areas. She would calculate the amenity value of a given choice S_k as $Z_1 = 3q_1 + 4q_2$. The second decision maker is depicted as having a more narrowly defined sense of aesthetics: high values are placed on uncut natural forest and low values on managed areas and areas heavily utilized by people, resulting in his calculation of the aesthetic goal as $Z_1 = 1.0q_1 + 10q_2$. The differences in goal calculations only repeat the old saying "beauty is in the eye of the beholder;" they also are the reason why the multiple decision maker problem, once it is granted that all viewpoints are legitimate, will be difficult to resolve.

The outputs are weighted by the relative value weights for each goal of each decision maker (table 5). When the feasible region in objective space is mapped into decision space, a different map is created for each decision maker such as shown in figure 3. The decision makers again examine the feasible region with their utility functions and make a choice. In this example decision maker 1 switched from S_7 to S_2 after the more detailed evaluation while decision maker 2 maintained his

Table 5.--Value of outputs in objective space for two decision makers.

Aggregate choice	Decision maker #1		Decision maker #2	
	Income goal	Amenity goal	Income goal	Amenity goal
S1	5760	3800	3700	4820
S2	6560	4500	4300	5920
S3	4960	3900	3500	5720
S4	4160	3600	3100	5620
S5	3360	4110	3300	8520
S6	5120	4090	3580	5740
S7	5970	4590	3980	6790
S8	4330	3990	3380	6640
S9	3420	3590	2980	6540
S10	2720	4090	3180	9440

The objective values are calculated using the criterion coefficients from Table 4 and the outputs for the aggregate choices in table 3.

Decision maker #1

Income goal value = 8Q1 + 0Q2
Amenity goal value = 3Q1 + 4Q2

Decision maker #2

Income goal value = 4Q1 + 2Q2
Amenity goal value = Q1 + 10Q2

choice of S_{10}. The indirect approach does not avoid the necessity for the decision makers to subjectively weight the different goals. It only provides the decision maker more information and experience before the weights are assigned.

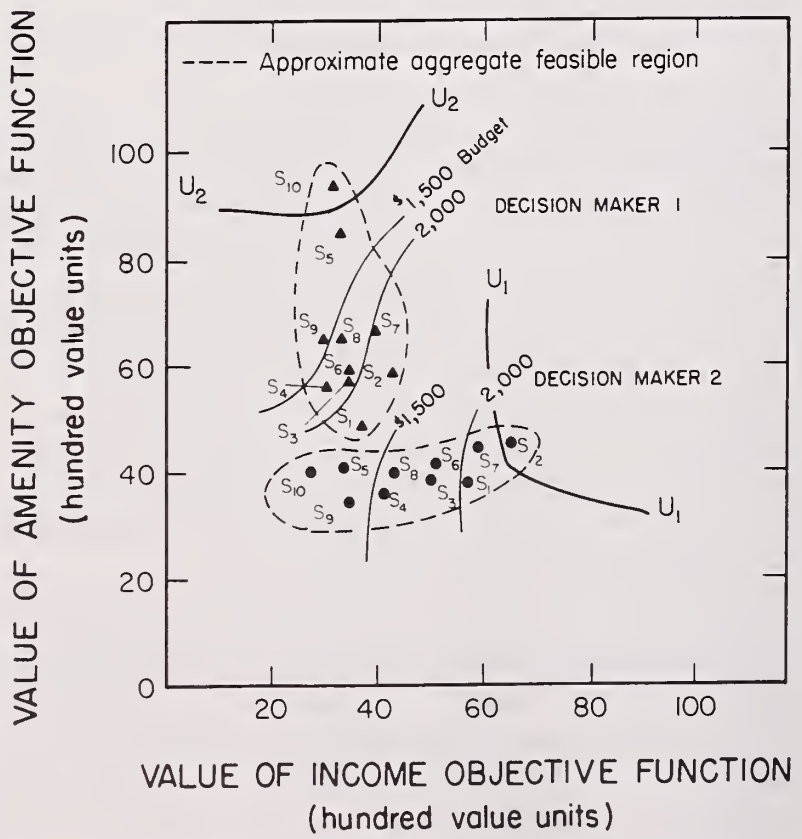


Figure 3.--Aggregate choice feasible regions mapped into objective space for two decision makers.

It's not clear to me whether participants in IFSP negotiations will want to use direct or indirect approaches. Probably some of both. The answer to this will not be known until the people involved are actually assembled and we learn their analytical comfort levels and they decide how they want to deal with the problem. Each group of participants will surly approach the problem in a unique way.

The process of identification of participant goals to select the most important outputs for quantification, and assembling unit plan options into aggregate choices to create a feasible region in decision space are common needs. These will constitute the principal analytical demand on an information system to support integrated Federal State planning. If, in addition, participants wish to use more formalized evaluations and tradeoff analysis to support their negotiations, then the information system can be usefully augmented by selected search, generation, filtering, optimization techniques of multiobjective programming (MOP).

Outline of a Likely Interactive Analysis and Negotiation Process for Integrated Federal-State Planning

Although the primary focus of this paper is designing an information and analysis system to support IFSP, design needs to anticipate the most likely ways in which the system will be used. The first and most basic assumptions are that laws, statutory authority, and political reality will allow a meaningful negotiating process to exist, and that important participants will have reason to come to the negotiation table. To be meaningful, I mean that *participants must feel that within the negotiation process they have significant power to affect the outcomes.* Practically, this requires that representatives of different agencies, owners, institutions, and affected interests, both public and private, have the incentive and authority to sit down and "make deals" to transfer resources, increase budgets, change regulations and laws, and link plans in order to achieve common, agreed upon goals. Meaningful negotiation is very different than the current "comment" approach where affected interests and decision makers comment on proposed plans of others but each planning unit manager makes almost fully independent decisions. The real power of the commentator is the implied threat of bad publicity, political pressure, or legal challenge.

Given that meaningful IFSP can exist, one scenario is outlined to suggest how negotiations might progress and interact with an information and analysis system. It assumes that the full scope of interested and affected interests are identified, classified, and a representational scheme agreed upon and that a manageable hierarchy of committees and negotiators is established. The process itself is conceptualized as a continuous series of short term planning cycles. During each 5- to 10-year planning cycle the participating negotiators strive to reach rough agreement on a long term collective land use strategy and more specific agreements on the activities, resource transfers, policies and programs to be implemented in the next 5- to 10-year period.

At the beginning of a planning cycle, analysts are assumed to have assembled available data and constructed an information base that describes the finite set of existing individual and aggregate planning unit choices, outputs and consequences. At this point the idealized 10-step procedure outlined below starts. Each step of this procedure is described and then illustrated with further development of the example started in tables 1-4 and figures 1-3.

Step 1. The negotiators invest in training to understand the character of the IFSP problem, some analysis basics, an how negotiation can work and benefit the participants. Training games using hypothetical or remote data sets could play a big part in this training, orientation step.

Step 2. The negotiators invest in learning the quantitative dimensions and important tradeoffs found in the existing feasible region for the IFSP problem of their State (fig. 2).

Step 3. The difficulty of evaluating Statewide aggregate choices without information for some planning units becomes intolerable to the participants. Estimates, however rough, are made of the most important outputs under existing management from the missing management units. For the example, this means Unit 4, the nonindustrial lands unit, is briefly studied and is estimated to provide 200MMBF of timber and effectively set aside 100M acres of unharvested large timberland. This new information results in an augmented and revised feasible region (fig. 4).

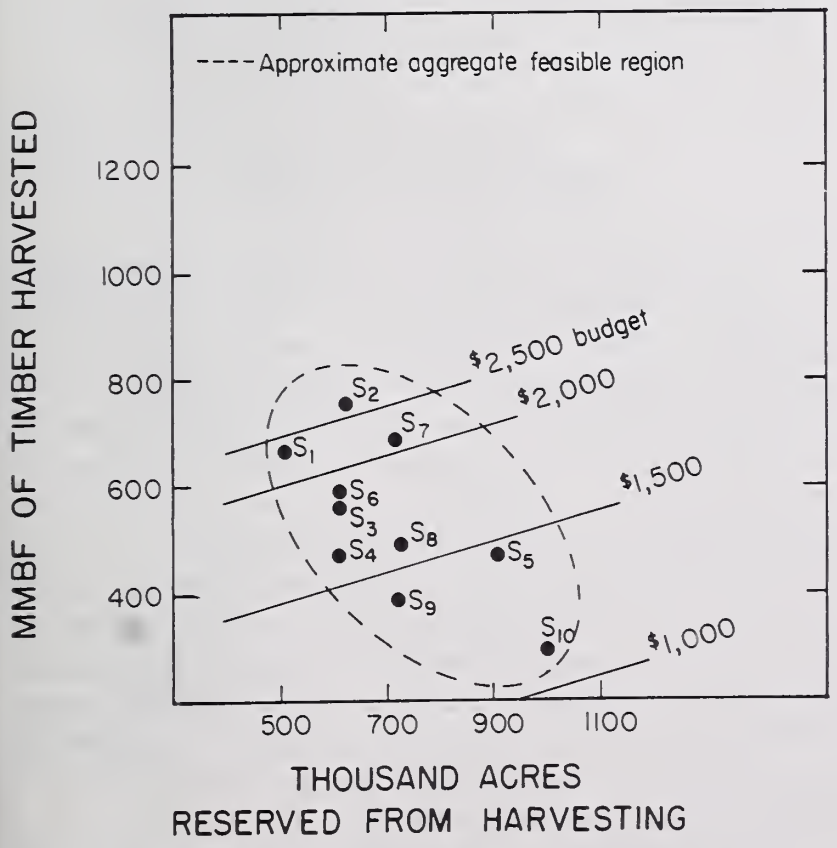


Figure 4.--Aggregate choices augmented by an alternative for the non-industrial planning unit.

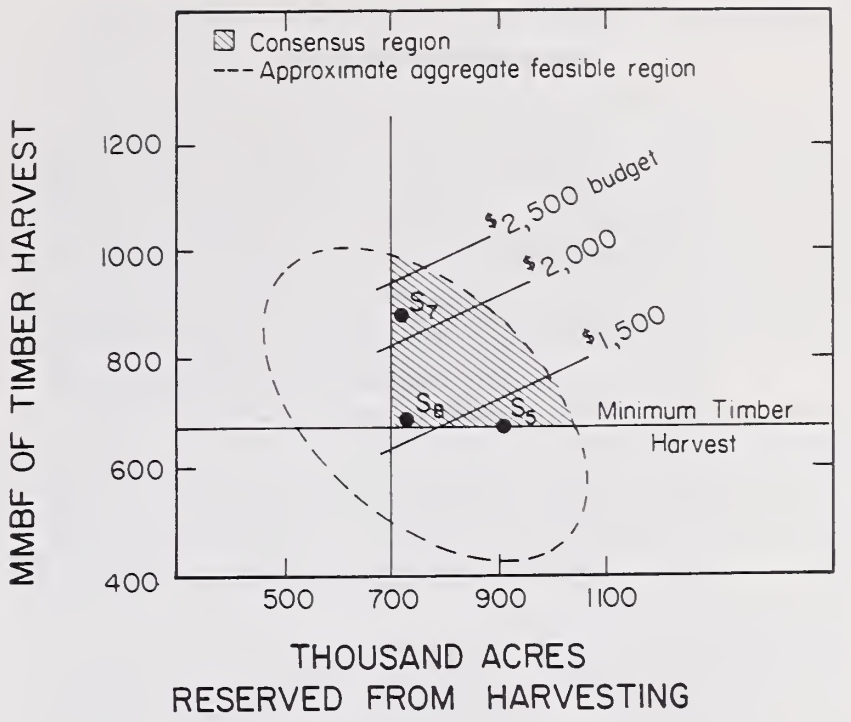


Figure 5.--First round consensus region negotiated in decision space.

Step 4. The negotiators attempt to delineate a subset of the augmented feasible region in decision space that is minimally acceptable to all interests represented. This highlights communication and procedural problems, identifies additional information needs, and help focus the more detailed examination and evaluation at subsequent steps. For the example, suppose a series of negotiations reveals that the minimum acceptable timber supply to the most demanding timber negotiator is 680MMBF and the minimum acceptable area to the most demanding amenity interest is 700M acres reserved from final harvest, creating the reduced feasible region in figure 5.

Step 5. To ensure that all important aggregate choices are politically and technically realistic, negotiators critically review the existing feasible region for accuracy and adequacy. Is it reasonable to assume that all existing planning unit choices are feasible? Which are suspect and which need more study? Are some aggregate plan options infeasible for political or legal reasons, or in terms of their assumed resources? If so, some planning unit choices may be deleted, aggregate constraints changed or added and the aggregate feasible region appropriately reduced. In the example, aggregate budgets of greater than $2000 are judged pragmatically unrealistic. Additionally a more careful analysis of available large timber acreage suitable for non timber harvesting reserves to be somewhat less than first estimated. A new maximum estimate of 900M acres is accepted by the negotiators (fig. 6).

Step 6. Existing unit plan options are examined to determine if they represent a full range of all possible feasible choices. Moreover, if additional aggregate resources and new multi-institutional arrangements are made available, what new choices are possible? This step results in direction to the analysts for generating new management unit choices to aggregate and augment the initial consensus feasible region. In the example, higher state budgets and a coordinated political effort is estimated to raise the aggregate budget constraint from $2000 to $2500. Innovative new alternatives for individual planning units are identified based on tradeoffs and linkages between planning units which provides the new aggregate choices S_{11} - S_{15} (fig. 7).

Step 7. In a series of negotiating rounds the augmented feasible region of step 6 is again reduced to a subregion that meets the realistic minimum or maximum bounds of all negotiators. A variety of generation, filtering and multiobjective programming techniques may prove useful to the negotiators in facilitating this process. The desired result is a consensus region containing a subset of aggregate choices from which a final choice will likely be made.

Step 8. Develop the "deals" between participants that provide the needed incentives and compensations to permit a specific choice to be selected and implemented. Additional MOP can be used here.

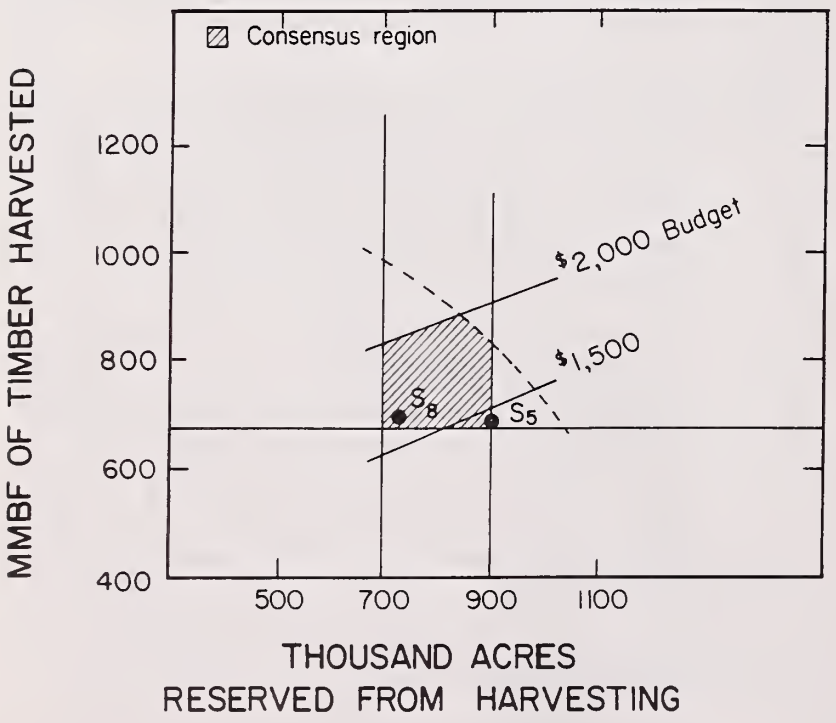


Figure 6.--Reviewed and revised consensus region in decision space.

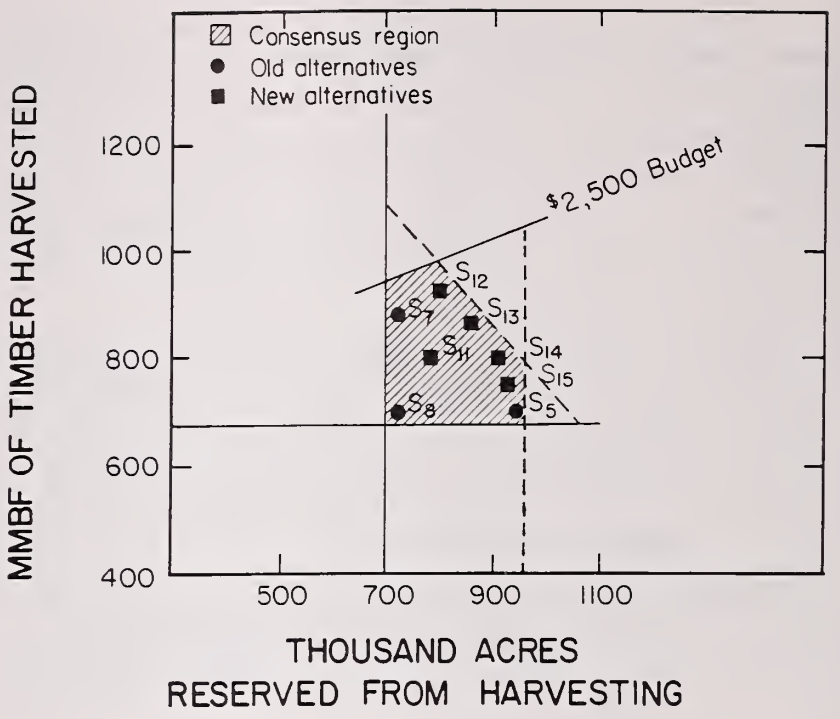


Figure 7.--Augmentation of revised first round consensus region to initiate second round negotiation.

Step 9. Final decision. Initiate the aggregate level resource and institutional arrangements needed to implement the selected choice for each planning unit. The decision itself will more than likely consist of partial coordination of some ownerships and the implementation of some new governmental policies and programs. Many ownerships will retain and implement their original preferred alternatives.

Step 10. Monitor and Continue, starting the next 5-10 cycle.

Available Analytical Methods

A substantial literature has emerged since the early 1970's showing many problem formulation strategies and optimization algorithms to deal with multiple objective problems. Virtually all of this material addresses public and private land management problems as single decision maker problems with and two or more goals. Goal Programming is the multi-objective programming (MOP) technique receiving the most application in Forestry (Arp and Lavigne 1982, Bell 1976, Dyer et al. 1979, Field et al. 1980, Walker 1984). Steuer and Schuler (1978) used an interactive interval criterion weights/vector maximum approach for public land planning problem but considered the forest planning team to be "the decision maker." Hotvedt et al. (1982) used a heuristic interactive procedure to develop goal weights from the preferences of several different persons working for the same private timber corporation.

The IFSP problem, as defined earlier in this paper, implicitly or explicitly has *multiple decision makers*. It will be "solved," if

it can be solved, only through political negotiation. Cohon and Marks (1975) in their early multiobjective programming review paper recognize this important distinction and comment that when political feasibility is a primary consideration, it requires "definition of the next problem in public planning: the multiobjective multiple-decision maker problem."

Steuer (1986) has organized the fast developing field of multiple criteria optimization and provides an accessible body of principles in an effective textbook. Indirectly, however, he offers little hope for direct application of multi-criteria optimization techniques to the IFSP problem. In the introduction to his book he suggests that "whereas multiattribute decision analysis (which addresses problems with a small number of alternatives in an environment of uncertainty) has been most applicable in resolving difficult public policy problems...multiple criteria optimization is more useful with less controversial problems in business and government."

The IFSP would surely have to be classed as a highly politicized, "difficult and controversial public policy problem." In addition to multiple decision makers it has the full compliment of fuzzy (Bellman and Zadeh 1970) and wicked (Allen and Gould 1986, Liebman 1976) problem properties.

I have found few definitive suggestion in the operations research literature for dealing with the multiple decision-maker, multiple criterion problem, nor would I expect to. Using single decision maker optimization techniques for a multiple decision maker problem implies either *unanimity* or a negotiated *consensus* of all participants on goal levels, weights, and priorities. If such consensus is not forthcoming, the optimization techniques are strictly limited to an information generation role. By solving over a series of alternate goal and value structures, participants can be made much better informed of the shape of the feasible region in decision and objective space for themselves, and for each of the other participating interests. This may facilitate the negotiation and search process to find a consensus position.

To work with the IFSP problem, we may have to abandon insistence on considering only efficient solutions, because a given aggregate choice that is dominated in decision space may be non-dominated in objective space by decision makers that assign negative utility to some outputs and activities such as clearcutting. Similarly, the notion of optimality, if pushed too hard, may only serve to muddy communication between participants.

Setting aside the analytically powerful concepts of efficiency and optimality leaves little theoretical purity and analytical elegance, but systems analysis and operations research has this important job of helping society deal with very important multiple decision maker land management problems. The role of analysis will become more to define problems, to educate political participants, and to provide support information to facilitate interactive negotiations among people, some of whom are guided as much by emotion as the intellect in developing their positions.

A Modified Goal Programming Model for Integrated Federal-State planning

Bearing in mind the preceding definition of the Integrated Federal State Planning problem, the negotiation procedure scenario, and the inherent limitations of single decision maker optimality analysis when dealing with multi decision maker problems, a traditional goal programming formulation was modified to serve as an information system for the problem and negotiation procedure defined above.

Since each planning unit works up one or more discrete plan choices, these are viewed as package deals where any one alternative must be implemented completely or not at all. Hence this problem formulation treats each public planning unit alternative as a 0,1 integer variable. All alternatives for a given planning unit are mutually exclusive and only one plan can be chosen for implementation. All private land ownerships within a defined geographic area are classed as industrial or non-industrial, and each class is treated as a planning unit. Alternatives for the private planning units are different scenarios for how these lands will be owned and used in the future under existing and new policy packages. Accounting variables are defined to accumulate, for reporting and constraining purposes, the production of outputs, activities and consequences of interest from regional and statewide aggregations of the public and private forest planning units.

Goals are entered in combinations of four ways: (1) in the objective function as a weighted function of selected activities or outputs, (2) in the objective function as weighted deviations from desired levels of selected forest outputs, (3) as mandatory constraints on output or activities such as a minimum timber harvest or maximum acres clearcut in a region, or (4) as constraints that force pre-selected unit plan alternatives into solution.

Such a flexible goal structure can swing from single goal maximization, to a traditional goal program, to a pure simulation that calculates consequences of exogenously selected and hard-wired alternatives. The method of formulating goals and objectives will depend on how the people representing affected interests feel about articulating and negotiating their goals. Perhaps more importantly it will depend on their individual perceptions of the relative power they can achieve within negotiation vs. the power they can achieve through legal action, political influence and other means of achieving desired goals.

Aggregate Choices from California's National Forests: Some Initial Results of a Case Study

All planning choices in published DEIS for the 17 California National Forests were extracted and assembled in the goal programming framework outlined above. Each plan for each forest was treated as a mutually exclusive integer choice and the program was required to select one plan from each forest. Data on 6 priced and about 30 non-priced National Forest outputs was

included and tracked by four sub-regional groupings and totaled for the state in each of the first 5 decades covered by the plans. The "most likely" California FRRAP Assessment estimates for timber and forage outputs for these regions and time periods were also included in the model. Since at the moment we only have one private sector scenario, it is effectively a constant and therefore these initial results only look at tradeoffs within National Forest lands.

Exploring the Feasible Region

To initiate analysis, the feasible region of all possible aggregate choices from the National Forests was examined. To do this, the objective function was first set to individually maximize and then to minimize each of the six priced outputs plus retention acres and budget. The results of these independent maximizations and minimizations are shown in table 6. As we had suspected, the dispersed recreation showed little variation across all plans and developed recreation and anadromous fish but little more. Grazing and timber showed about a 50 percent increase from the minimum to the maximum. The timber range was calculated after the approximately 2000 MMBF cut of the private lands are subtracted from the total. Water outputs were measured as increments over the historic 70 million acre feet baseline level. As a percent of the base level, the most water productive set of National Forest plans only increase water by an estimated 525 thousand acre feet or a 0.6 percent increase over historic levels. Retention acres, those acres allocated for visual management purposes under sharply restrictive timber harvesting prescriptions, varied almost fourfold over the aggregate choice set and appear to be one of the most important tradeoffs with the commodity outputs. Appropriated budget costs of the alternatives also ranged substantially, nearly doubling in real dollar costs in each decade from the least to the most costly set of alternatives.

Table 6.-- First decade maximum and minimum output levels possible in Region 5 From current DEIS forest plan alternatives.

Output	Units	Decade	Min.	Max.	Max/Min
Anadromous fish	M lb.	1st	2796	3238	1.15
Dev. rec.	M RVD	1st	11164	14324	1.28
Dispersed & wild rec.	M RVD	1st	30035	32056	1.067
Grazing	M AUM	1st	520	739	1.42
Fed timber	MMBF	1st	1617	2523	1.56
Oth. timber	MMBF	1st	2000	2000	1.00
Total water	M ACFT	1st	70077	70525	1.006
Water incr	M ACFT	1st	77	525	6.82
Retention area	M Acres	5th.	1347	5116	3.80
Operating	MM	1st	248	401	1.62
Cost	1982$	2nd	273	422	1.54
		3rd	299	488	1.63
		4th	314	536	1.71
		5th	341	633	1.86
		current	300		

The tradeoffs between retention acres and budget costs and all other outputs and activities were evaluated. Using the data of table 6, five levels of budget were scaled at even 25 percent intervals between the maximum and minimum cost. Similarly five levels of retention acres were scaled between maximum and minimum levels. The objective was set up as a normalized goal program that minimized the unweighted sum of the percent underachievement of the maximum possible physical output levels for fish, timber, grazing, water, developed recreation, and undeveloped recreation. This objective treats all goals as equally important and is indifferent to goal overachievement. In this case, the aggregate goal of achieving all maximum outputs defines a solution outside the feasible region.

Five problems were solve using only the retention constraints. A second set of five problems were solved using only the budget constraints. Finally the retention constraint was set at each level and solved for each budget constraint level in a set of 25 runs to determine the joint impacts of the two constraints. In terms of the 10 step analysis and negotiation procedure previously outlined, this analysis only carries through step 2, the familiarization with the feasible region.

Retention Analysis

The five runs sequentially set a minimum required constraint on aggregate retention acres. The pattern of individual National Forest plans selected in the optimal solution is shown in table 7. Reading a row or column moving from left to right we see what happens as the retention constraint is relaxed from its maximum level of 5.1 million acres to the minimum level of 1.37 million acres. Predictably we start out with amenity and low budget alternatives for nearly all forests and then move to the higher timber output market, RPA and maximum cash receipt alternatives as the constraint is relaxed. Note that some forest such as the El Dorado and Lassen the high timber output alternative enters solution as soon as the constraint is relaxed one step. This likely means these forests have the highest direct rates of tradeoff between timber and retention acres.

In figure 8, the tradeoffs of primary outputs are shown measured in terms of percent achievement of maximum possible output levels. The tradeoff with timber is nearly linear over the region and range of retention acres. Since retention acres are presumably intended to be a proxy for visual management decisions and visual values, then visual vs. commodity poses a clear tradeoff. Yet this tradeoff is not clearly or forcefully articulated in many DEIS. The retention area tradeoff with a timber linked secondary output, county % tax receipts, is shown in figure 9. The partitioning of receipts by sub state region shows the timber rich Northern California to receive most of the county tax receipts.

Table 7.--Forest plan alternative selected at different levels of aggregate retention area constraints.

Planning unit	RET1	RET2	RET3	RET4	RET5
Retention acres	5116	4174	3232	2289	1347
National Forest	------Alternative Selected----------				
Angles	PRO	MKT	MKT	MKT	MKT
Cleveland	PRF	PRF	MKT	MKT	MKT
El Dorado	PRF	MKT	MKT	MKT	MKT
Inyo	AMB	PRF	PRF	RPA	RPA
Klamath	CEE	CEE	CEE	CEE	CEE
Lassen	AMN	RPA	RVW	RPA	COM
Los Padres	NOW	NOW	NOW	WLD	MKT
Mendocino	AMN	AMN	AMN	AMN	MKT
Modoc	AMN	AMN	AMN	RPD	IND
Plumas	AMY	AMY	CEE	CEE	CEE
San Bernardino	CUR	CUR	CUR	CUR	RPA
Sequoia	AMN	PRO	PRO	PRO	PRO
Shasta Trinity	MIX	MIX	CUR	CUR	CUR
Six Rivers	LOW	PFO	PFO	RPA	RPA
Sierra	LBU	PRO	PRO	PRO	PRO
StanislauS	ALT#A	ALT#A	ALT#G	ALT#G	ALT#G
Tahoe	AMN	AMN	RPA	TMB	TMB

Budget Analysis

It is recognized that most of the National Forest alternatives were developed without using budget constraints and that this has some merit as a budget planning device. However the State and the affected private interests also need to plan and respond

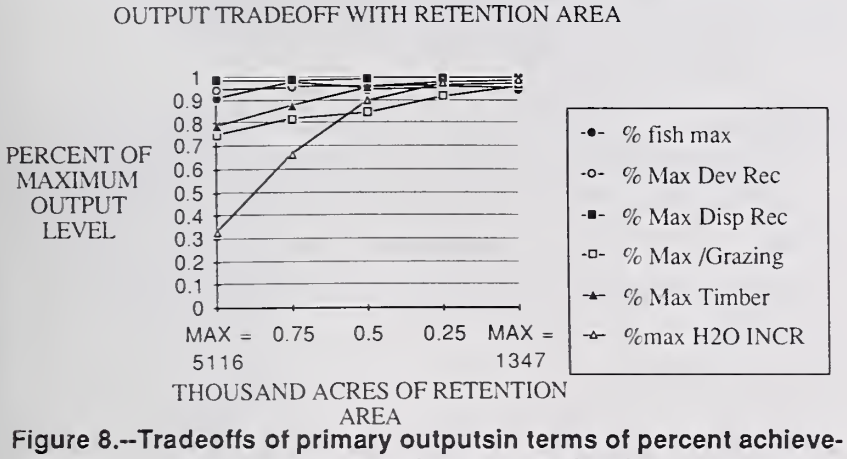


Figure 8.--Tradeoffs of primary outputsin terms of percent achievement of maximum ouput levels.

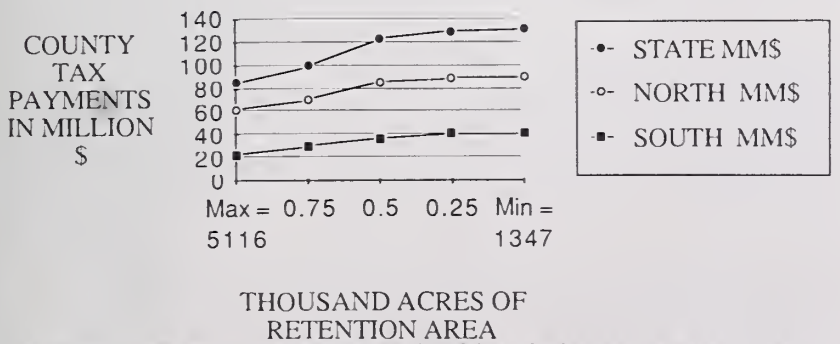


Figure 9.--Retention area tradeoff with a timber linked secondary output (county tax receipts).

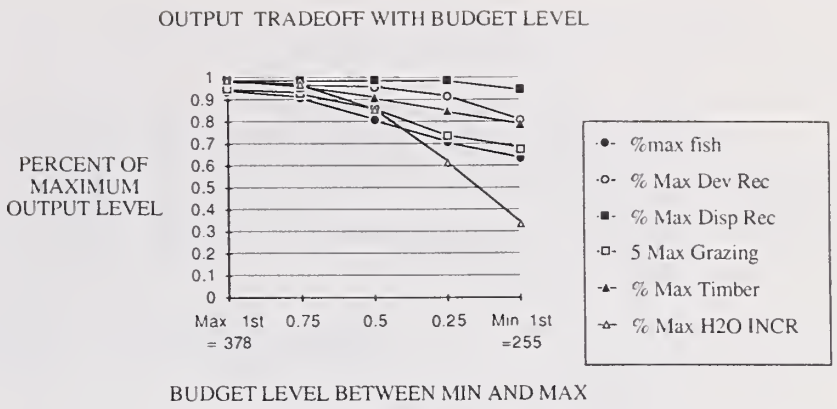


Figure 10.--Primary outputs at different regional budget levels.

pragmatically in terms of what they think the *actual* output levels from the National Forests will be. We have moved through nearly a decade of budget and personnel reductions and the Federal debit and financing picture is not one to encourage even committed optimists. It therefore seems prudent for the State and others to evaluate the current program plans of the Forest in terms of their costs and against what pragmatic estimates of future appropriated budgets will be. The primary outputs provided by the R-5 at different levels of budget are graphed in figure 10. The current budget of R-5 in 1982 dollars is approximately $300 million. This is shown on figure 10 as the vertical line BB. Water, grazing and timber again show significant responsiveness to budget. (Remember there is no retention constraint in any of these runs.)

The overall responsiveness to budget is substantially reduced for all outputs by the time 80 percent of the maximum cost budget is available. With this set of alternatives, additional increments of budget do not stimulate large changes in the outputs. It might be hard to justify the last increment after 90 percent of the high cost budget is reached.

At current 1982 budget levels the Region cannot finance the Preferred alternative for each Forest. Hence the State and others want to know what set of plans will be implemented if funding at around the current level is continued. To make the best use of limited funds, a different set of alternatives for each Forest needs to be generated. For a start, all the current alternatives could be reevaluated in FORPLAN using the current, slightly higher, and slightly lower budget levels constraints.

Joint Retention-Budget Analysis

For the joint analysis, the budget constraint was varied over all its levels for each level of retention area constraint. The level of timber harvest associated with these joint constraints is shown in figure 11. At retention levels of 5.16 and 4.17 million acres, timber is generally unresponsive to budget after the first budget increment. At retention levels of 3.2 million acres or less, there is a significant constant retention effect but timber shows an almost linear response to budget and, presumably, investment in timber production.

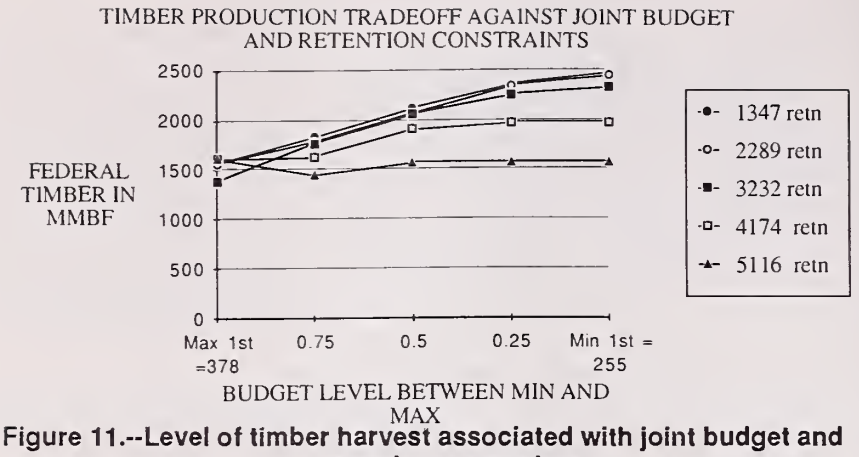


Figure 11.--Level of timber harvest associated with joint budget and retention constraints.

Water increments show about the same pattern as timber: little responsiveness to budget at the two highest retention levels and reasonably strong responsiveness at lower retention levels.

These joint results suggest that, given available forest plan options, increases in retention acres above about 3 million acres may have high marginal opportunity costs in terms of primary output production and general efficiency of budget use. Analysis to find out the causes+for these tradeoffs and interactions would be interesting. I cannot explain these timber and water results further without a thorough spatial study and evaluation of how each individual forest handled their visual management planning and how the retention and partial retention areas interfaced with timberlands and productive snowmelt areas. The DEIS numbers we see were, of course, filtered through the FORPLAN representation of the spatial problem and perhaps something was lost in the translation.

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Modeling Local Timber Economies for Land Management Planning, Policy Studies, and Timber Supply Analysis

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Abstract.--The Oregon State Forestry Department, the Pacific Northwest Region and the Pacific Northwest Research Station of the USDA Forest Service, and the Bureau of Land Management, are collaborating on a project to prepare a computer model of Oregon's timber economy. The model will facilitate land›management planning, policy analysis, and timber›supply studies. The model portrays the interactions between timber owners, wood›products manufacturing mills, and the domestic and international demand for products produced in Oregon. A test of a prototype model, along with suggestions for further research, including a probabilistic portrayal of harvesting and management on private forestland, are given in this paper.

What assumptions should planners and analysts make about the future demand for timber on the National Forests? What do the different land and resource management alternatives for the National Forests mean for timber harvest, stumpage prices, employment, and wood products manufacturing in the resource›dependent communities of the Pacific Northwest? Local›market modeling research at the Pacific Northwest Research Station should help the public land›management agencies and others answer these questions.

We are collaborating with the Oregon State Forestry Department, Bureau of Land Management, and the Pacific Northwest Region of the USDA Forest Service, to develop an operational model of the local timber economies in Oregon. The model will approximate the way actual markets work by portraying the physical production opportunities confronting timberland owners and wood products mills, and the economic and social forces affecting stand›management, harvesting, manufacturing, and plant-investment decisions.

Three broad purposes influence the design of the model: land›management planning in the public sector, analysis of policies affecting the timber resource, and analysis of future timber supply. Historically, analysts at the land›management agencies and the Pacific Northwest Research Station have used different techniques to prepare projections of timber supply and to analyze the consequences of land management and policy choices.

The local›market model project is an outgrowth of the agencies' desires to prepare mutually understood analyses of where Oregon's timber economy might go in the future. The specific purpose of the project is to prepare a computer model that can be used to prepare a broad range of technically defensible evaluations of public and private forestry alternatives.

As a first step in the project, we developed a prototype model of the local timber economies of southwestern Oregon. The model was implemented with the Generalized Equilibrium Modeling System (GEMS), a flexible system for modeling the interactions between timber suppliers, mills, and the final demand for wood products (Boyd et al. 1983). Projections of prices and quantities prepared with GEMS are conceptually appealing because they represent intra- and intertemporal equilibria between supply and demand across product and factor markets. Much of the remainder of the paper discusses the design and implementation of the prototype. The prototype is one of two major influences on our research.

The second major influence, also discussed, is the experience gained from implementing a simulation model of local supply and demand of timber in Oregon and Washington. We implemented the simulation model with DYNAMO, a software

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system for modeling systems dynamics problems (Richardson and Pugh 1986). At first glance, the simulation model appears to be a crude local›market model because it portrays only timber supply and demand, lacks a manufacturing sector, and only approximates the intra- and intertemporal equilibrium between supply and demand that is called for by natural resource theory. The simulation model is important, however, because it includes two features that were not part of the prototype local›market model's representation of timber supply: (1) the model incorporated our full knowledge of the variation in the physical condition of the industrially owned resource, and (2) the model's structure opened up interesting possibilities for using statistically estimated probabilities to model harvesting and stand›management behavior.

Work is progressing to exploit the lessons learned in designing and implementing the prototype and simulation models. We conclude our paper with a view of where local›market modeling work is headed in the future, both as a researchable problem and as a tool for State and Federal planning, policy analysis, and timber›supply studies.

What Purposes and Issues Motivate Local-Market Modeling?

The need for better land›management planning, policy analysis, and timber›supply projections motivates local›market modeling research. Some specific issues the local›market model is designed to address are worth considering; the list of issues suggests the capabilities and technical requirements of the model.

Land›Management Planning

If you were on the planning staff of the Umpqua National Forest, headquartered in Roseburg, Oregon, you would be interested in the effect that each of the alternatives in the Forest Plan might have on the local wood›products industry and its associated employment and income. The results of such an assessment may not be obvious because the industry is confronting complex changes in raw material availability and quality, manufacturing productivity, and demand for its products. A knowledge of the management choices for the Umpqua, the role of the Umpqua and other forested land in supplying timber to meet the demands of the local wood›products industry, the characteristics of the industry, and the external forces affecting the industry are necessary to address this issue.

Policy Analysis

Policy analysis may require a knowledge of the timber economy that is comparable to the understanding implied by land›management planning. Policy issues commonly apply across ownerships and across management-unit boundaries. For example, management of the northern spotted owl and the transition from an old›growth to a second›growth economy are related policy issues that transcend unit boundaries and the different forest ownerships. Much of the owl's habitat is in old›growth stands located on Federal lands in western Oregon. Because old›growth is unevenly distributed, some communities can expect to feel more heavily than others the effects of management measures that restrict old›growth harvest to protect owl habitat. To address these effects, one needs to understand the probable management strategies that the public agencies might adopt, and where and when these strategies might be implemented.

Timber›Supply Analysis

Timber›supply analysis requires an understanding of the variation in the timber resource and the differences in opportunities, policies, and objectives that affect the behavior of public and private forestland owners. All agencies collaborating on the project have an interest in the timber›supply situation in Oregon. The Forest Service and BLM are committed to consider supply›related issues in their plans. As a complement to the plans for the individual National Forests in Oregon and Washington, the Forest Service has prepared an assessment of how the plans can be expected to affect local, State, and regional harvest on all ownerships during the period covered by the plan, and how the plans can be expected to influence the supply possibilities for the ensuing decade. The Oregon State Forestry Department must comment on the Federal plans and prepare an independent assessment of the future of Oregon's forest resources (the Forestry Program for Oregon). Finally, analysts at the Pacific Northwest Research Station must assess the implications for future timber supply in Oregon of data collected on non›Federal ownerships.

Conclusion: The Market Model as a Common Means to Address Timber-Related Issues

The market model will be a tool that each agency can use to prepare analyses that can be understood by the other agencies. Results will be technically consistent with the opportunities and behavior of timber suppliers, mills, and wood products markets. Users will be able to display simultaneously the local, State, and regional consequences of public and private forestry alternatives.

Each public agency can bring its perspective to planning, policy, and supply›related issues. The perspective of the Federal land›management agencies is to know where the Federal lands and resources fit in an economy that has extensive, privately owned timber lands and resources. The analysts at the Pacific Northwest Research Station and colleagues in the private sector want to know where non›Federal forests fit in an economy

whose future depends importantly on Federal forestry. The Oregon State Forestry Department wants to constructively evaluate Federal planning alternatives, and provide a credible, comprehensive view of the entire Oregon timber situation. Common to each perspective is a set of factors--notably the productivity and technology of the processing industry and the demand for manufactured wood products--that influence forestry and the forest industry but that are not subject to control by land managers.

Design of the Prototype

We identified six design criteria before work began on the prototype. The design criteria were the link between the model's purpose and its technical implementation. The design criteria also served as evaluation criteria; if we had been unable to implement any one of the six, we would have (in the best case) returned to the drawing board, or (in the worst case) aborted the project.

Portraying Supply and Harvest on Public Lands

We wanted analyses done with the local›market model to complement analyses of land-allocation and resource-scheduling choices. Therefore, we decided that the timber programs on the public land management units (National Forests, BLM Master Units, State Forests) had to be included in sufficient detail to capture the factors that influence the harvest of public timber. Examples of such factors are location, quality, and species characteristics.

To model public›sector behavior, we separated the public agencies' decisions to offer timber for sale from purchasers' decisions to harvest timber. This allowed us to treat the harvest schedule associated with a land›management alternative on a given National Forest as an intertemporally related family of supply curves. Demand, purchaser's willingness›to›pay for timber offered for sale, was modeled separately. No requirement was imposed on the market model that public timber offered for sale be harvested if no economic rationale existed for doing so.

Portraying Harvesting and Management on Private Land

We wanted the harvesting and management decisions of the industrial and farmer ownerships to be analyzed within the market model and consistent with economic opportunities to profit from growing and harvesting timber. This allowed us to represent behavior as a problem of optimally choosing among multiple harvest timing and management intensification options. We also decided, as an approximation to reality, that supply from the other›private ownership should be a insensitive to prices or other economic factors.

Portraying Manufacturing and Investment

We wanted both the decision to produce different manufactured products and the decision to expand or contract plant capacity to be analyzed within the model and consistent with economic opportunities to profit from manufacturing. This allowed us to project production and changes in capacity as a function of existing mill technologies, and changes in timber availability, conversion costs, product demand, and conversion efficiency.

Portraying Transportation Flows

We wanted to represent the flow of logs from the woods to major processing centers. This allowed us to explicitly represent transportation costs as a variable affecting harvesting, stand-management, product manufacturing, and capacity›investment decisions.

Portraying Market Equilibria

To achieve our goals of realistically portraying forest management and milling decisions, we wanted price and quantity results to be consistent with the intra› and intertemporal equilibria of supply and demand. This criterion required that supply and demand be in equilibrium across product and factor markets in any period, and that future prices and costs be considered in making harvesting, private stand›management, processing, and plant›investment decisions.

Sensitivity Analysis

The timber economy is a complex, dynamic system. The principal value of the local›market model is to learn how the timber economy will evolve as a function of different land›management options, different assumptions as to the behavior of landowners and millowners, changes in technology and utilization, and changes in wood›products demand. Therefore, the ability to evaluate efficiently a wide range of scenarios in an understandable, credible manner was a prime objective in designing the prototype.

Structure of the Prototype

The structure of the prototype model mirrored the structure of the actual timber economy (fig. 1). Demand for manufactured products, the processing industry, and timber supply were all explicitly represented; prices were the signals that affected management, harvesting, and investment behavior.

To implement the design criteria, we disaggregated this general structure to reflect differences in location, production

possibilities, and behavior of timber suppliers and the wood›products manufacturing industry. The disaggregation reflected the design criteria, the availability of data, and the structure of GEMS.

Timber Supply

We modeled separately the timber supply for industrial, farmer, other-private, and public owners.

The production possibilities for the industrial and farmer ownerships were represented using a stratum›based portrayal of the resource. Forest Inventory and Analysis (FIA) inventory data for these owners were delineated into strata defined by timbershed, productivity class, stand condition, and stand›age attributes. A yield schedule was prepared using DFSIM (Curtis et al. 1982) for each stratum comprised of precommercial stands. Strata characterized by more mature (natural) stands were projected using normal yield functions based on Bulletin 201 (McArdle 1927). DFSIM was used to generate a portfolio of managed yield alternatives, representing a range of management intensities, for acres regenerated after final harvest. For all strata, the yields were expressed not only as total volume by decade but as volume within three log›diameter classes.

Industrial and farmer owners within each timbershed were assumed to maximize present net worth by selecting an optimal sequence of harvest and stand›management activities. The optimization decision was based on maximizing current and future returns from harvesting and managing timber, and reflected the differential pricing of logs in each of the three diameter classes. Farmers were assumed to face a higher alternate rate of return than industrial owners. Harvest from other-private owners was projected as a constant volume equal to its trend over the period 1975 to 1984.

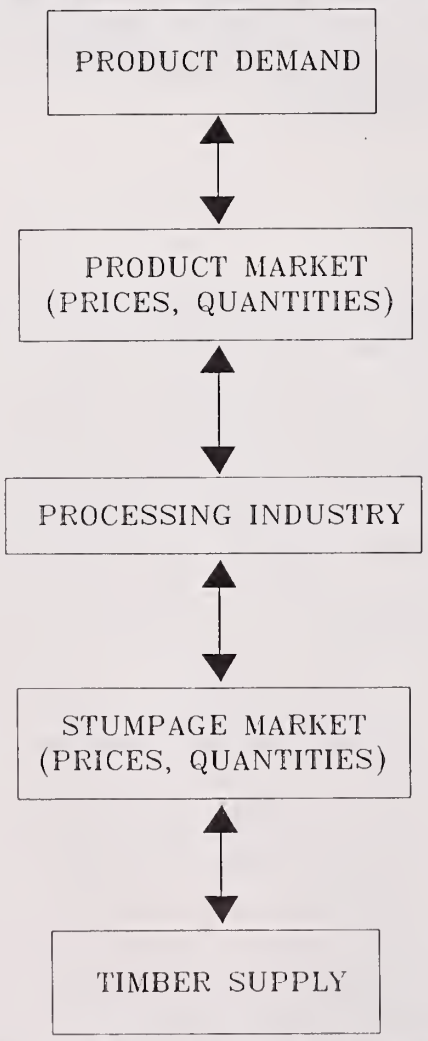


Figure 1.--The structure of the local›market model.

Supply curves, describing the relation between extraction costs and volume of timber offered for sale, by decade, were developed for three National Forests, five Bureau of Land Management Sustained Yield Units, and the Elliot State Forest. Extraction costs were defined as the costs, exclusive of stumpage, that timber purchasers would experience if they harvested public timber. The supply curves for the three National Forests were developed from preliminary harvest schedules and extraction costs prepared early in the current round of National Forest planning; supply curves for the BLM and State were developed from harvest projections reported in published plans.

Whenever the information was available, we prepared separate supply curves for existing stands, commercial thinnings, and the stands to be regenerated in the future. We also subdivided the Siskiyou National Forest into parts east and west of the Oregon Coast Range, and prepared separate sets of supply curves for each part. Volumes on each step of the supply curves were proportioned by the three log›diameter classes used to describe the private resource.

Public timber was assumed to be harvested from the quantities offered for sale, according to whether extraction costs were less than or equal to the value of the harvested timber. Therefore, though no assumption was made that all public timber offered for sale would be harvested, the supply schedule represented an upper bound on what the harvest volume could be during any decade.

The Processing Industry

We recognized two outputs (lumber and plywood) and three mill technologies (dimension mills, cutting mills, and plywood mills) for each of three processing areas in southwestern Oregon. The processing areas included all milltowns within a geographically defined area; the boundaries of the processing areas were drawn so that the mills in the included communities would have similar transportation costs from the many timber suppliers represented in the model.

Three manufacturing technologies were represented not only because each optimally produces a different mix of products, but because each optimally uses a different mix of log sizes. We modeled millowner decisions for each technology by assuming that they maximized profits based on the physical input/output efficiency of converting logs of different diameters, the costs of manufacturing (including the cost of expanding plant capacity), and the prices of manufactured products.

Implementing the Model with the Generalized Equilibrium Modeling System (GEMS)

We chose to implement the prototype model of the southwestern Oregon timber economy with the Generalized Equilibrium Modeling System (GEMS); GEMS is proprietary to Decision Focus Inc. of Los Altos, California (Boyd et al. 1983). The reasons for choosing GEMS were threefold: (1) the theory underlying GEMS--that markets tie together the separate optimizing behavior of many different parties--is intuitively and conceptually consistent with the way Oregon's timber economy works; (2) GEMS is a tested, flexible software system for analyzing the types of market›related problems confronting us; and (3) the solutions calculated with GEMS implement the theory of renewable natural resources in such a way that intra› and intertemporal equilibria across markets can be calculated.

GEMS is composed of three basic elements:

1. A library of generic subroutines or process models describing the behavior of different agents (timber owners, mills, and the demand for manufactured products) in an economy.

2. A network, specific to the model being implemented, describing the interactions among the processes. The GEMS network describes the timber economy as an economic system, and includes transportation links, conversion processes, and the feedback of price signals to influence what occurs in each process model.

3. An algorithm for determining the numerical values of all the variables in the model. Because forest›management and industrial-investment decisions are inherently forward›looking, we were seeking the GEMS capability for calculating intertemporally optimal solutions for particular process models.

A GEMS model is ideal for representing markets because it is not solved for the optimal behavior of an entire economic sector as a whole. Each process model represents instead individual optimizing behavior, and the model is solved for the dynamic market interactions of the collection of individually optimizing agents. The algorithm used to solve the model finds the set of variables (prices, quantities, management activities, and capacity additions) that satisfies the physical and behavioral relations embodied in the process models and the linkages among the processes.

The distinctive process model in the prototype model of the southwestern Oregon timber economy was private timber supply. It represented the variety of physical conditions and choices describing the industrial and farmer ownerships, by location, and, using optimal control techniques, modeled their harvesting and management behavior as a dynamic, profit›maximization problem.

Sample Results

Sample results from the prototype illustrate the capabilities we seek in an operation model of Oregon's timber economy.

Figure 2 displays harvest, by owner, for southwestern Oregon. The projections cover the next 50 years. The projections are the summation of public and private harvests, by local area. A parallel set of equilibrium stumpage prices was projected for each owner.

Figure 3 shows some of the detail that would be useful for land-management planning. The figure shows a comparison between the quantity of timber offered for sale on two of the three southwestern Oregon National Forests, and the quantity that is projected to be harvested from these Forests. The difference between scheduled and harvested is the result of the economically undesirable characteristics of the unharvested timber. This comparison highlights what is probably already known on those two Forests: that certain stands scheduled for harvest under current plans are economically marginal.

Figure 4 shows a comparison of the output of dimension and cutting mills over the next 50 years. Though total timber harvest will undergo a downward adjustment because of the falldown in

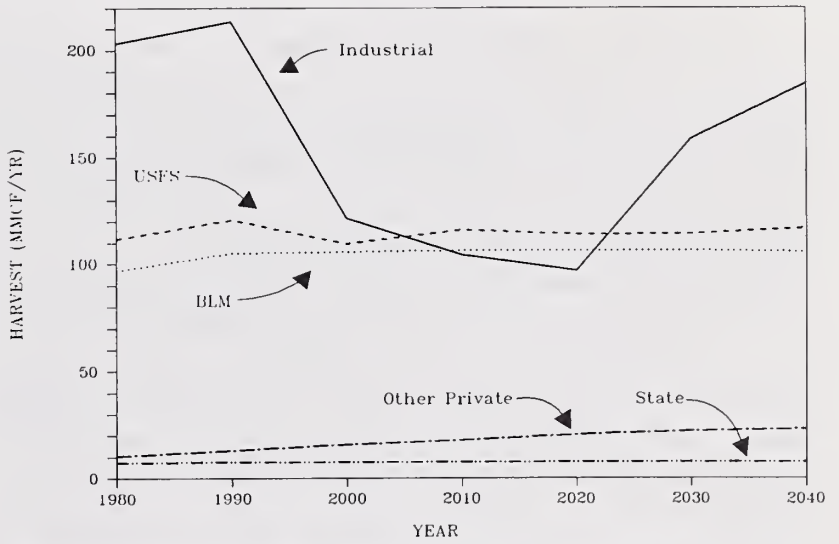


Figure 2.--Projected harvest, by owner, for southwestern Oregon.

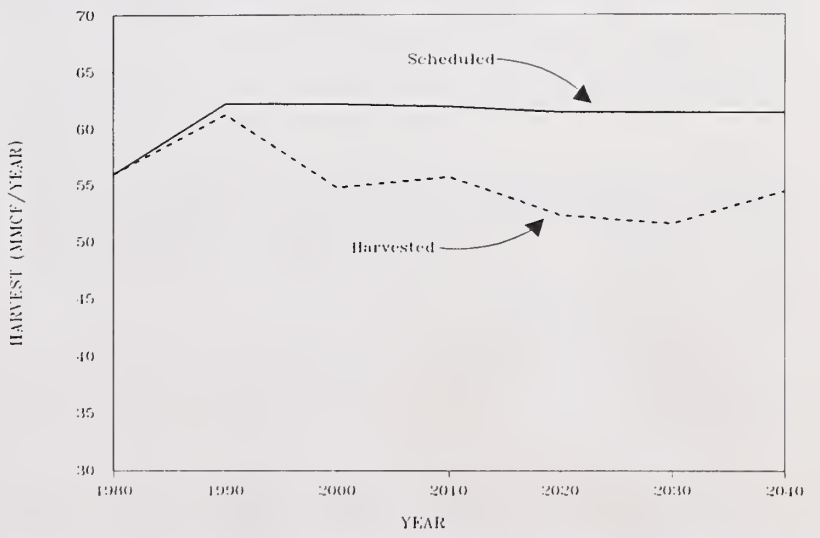


Figure 3.-- A comparison between volume scheduled for harvest and volume projected to be harvested on two National Forests in southwestern Oregon.

industrial harvest, the output of the different types of lumber mills will change dramatically as the quality and characteristics of harvested timber changes.

Cutting mills face an immediate falloff in production and employment. Cutting mills depend on the large diameter logs typically associated with old-growth. These mills produce a larger range of products, many having higher value, than do dimension mills. Employment per unit of output is also higher in cutting mills than dimension mills. The significance of figure 4 is that it demonstrates one possible future in the transition from an old›growth to a second›growth economy. The corollary to this drop in output is that cutting mills will depend primarily on Federal timber because the remaining old›growth stands are on Federal land.

These results were not intended as operational analyses of the southwestern Oregon economy because of the simplifying assumptions made for the prototype. These assumptions would necessarily be refined or discarded in an operational model, and data would be updated to reflect our latest knowledge of the resource, the processing industry, and the demand for products.

What Did we Learn from the Simulator?

The prototype model of the southwestern Oregon timber economy was well received by the collaborating agencies and other reviewers. But we learned some valuable lessons in 1987 from designing and implementing a simulation model of the demand and supply for timber in Oregon and Washington. Those lessons will affect future market›modeling work.

The simulator lacked many features of the prototype market model, and the use of DYNAMO imposed many more restrictions on modeling supply and demand interactions than was true with GEMS. But the simulator also incorporated an important enhancement: acreage represented by each industrial timberland plot (from the FIA database) retained its identity in the calculations of harvest and management. That is, for each plot on industrially owned timberland, we specified a yield (production) function consistent with the initial stand conditions of that plot. We used the Stand Projection System yield simulator (Arney 1986) to derive these functions by projecting the sample of trees measured on each plot.

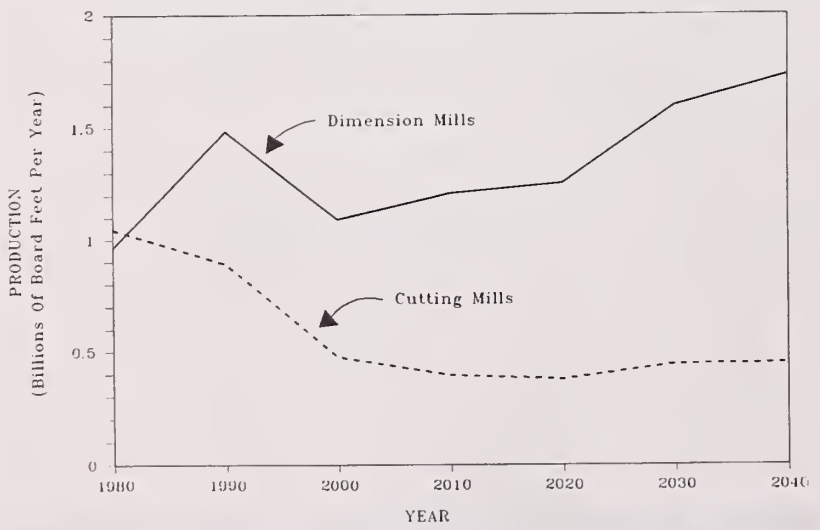


Figure 4.--Projection of production by cutting mills and dimension mills in southwestern Oregon.

The team found this plot›based approach technically feasible, computationally straightforward, and free of concerns on how to define strata that would adequately describe the variation in the privately owned resource. The method was realistic, exploiting to the fullest our knowledge of the variation within the industrial resource.

Harvest was simulated to occur in stands (plots) for which the returns from harvesting exceeded the costs of harvest plus the maximum profit foregone by not delaying harvest to a future time. The ability to portray industrial harvest within each timbershed was not impaired by using such a highly disaggregated representation of the resource. Industrial harvest was simply the sum of the volume harvested for each plot expanded by its appropriate acreage expansion factor.

Where are we Headed?

As we develop an operational model of the Oregon timber economy and move toward a similar model for Washington, further research will be required. We discuss six enhancements underway or contemplated.

Representing the Private Resource With FIA Plots

We believe that the plots›based approach to modeling the private resource is better than the stratum›based approach used in the prototype. The stratum›based approach required that we aggregate plots with similar characteristics and, therefore, represent all acres within the stratum with the same average set of yield attributes. The plots-based approach allowed us to retain our full knowledge of the variation and characteristics of the private resource and to tailor yield schedules specific to the initial stand conditions on the plot.

Probabilistic Representation of Behavior

Our portrayal of harvest and management behavior of private owners was broad, deterministic, and focused on long›run projections. The individual›plots approach presents innovative opportunities to achieve greater realism in portraying behavior and land›base shifts, and to calibrate projections during the first decade more closely to historical trends. Specifically, using probit and logit analysis and Markovian techniques, we will estimate the probabilities that a particular plot will be harvested or subjected to specific silvicultural treatments or shifted to a different owner class or land use. No comparable link between probabilistic behavior and a stratum-based approach is as easy to implement, because strata, unlike individual plots, are not sample observations for which probability functions can be readily estimated.

More Efficient Data Handling and Yield Projections

We are considering the construction of a preprocessor program that will efficiently specify alternative yield schedules for individual plots or strata. Currently, the local›market model requires a vast amount of yield›simulation work, all of which is done for a set of intensification scenarios by manually running an appropriate stand simulator.

Improved Representation of Diameter Distributions

Currently, the diameter distributions associated with any particular stand are crude. This information can be refined by exploiting available information measured for each plot about individual tree diameters and heights.

Expanded Representation of Manufacturing Options

We propose to model at least four different lumber products and two plywood products. The lumber/plywood dichotomy obscures some product niches for which Oregon's forests have a comparative advantage in providing raw material. We also intend to prepare scenarios that would recognize the introduction of new manufacturing technologies or product lines into the Oregon timber economy.

Improved Representation of Final Demand

We have underway a Delphi study of the future of the demand for several lines of wood products manufactured in the Northwest. The objective is to systematically sample recognized experts to understand their individual and collective opinions of the future of the demand for the Northwest's wood products. The study is being conducted by Jay O'Laughlin of Texas A&M University. We hope to make his results available to all users of the local›market model.

Conclusion

Experience with both the prototype and simulator have been encouraging to ourselves and others. Local›market modeling is technically feasible: the theory, techniques, and data are available to develop such models. More important, perhaps, the overlapping perspectives of the public land›management agencies on the resource management choices facing them can be technically accommodated within the framework of the model; the model, therefore, provides a mutually understood way to analyze a common set of problems.

An important question remains: "Are we simply replowing old ground with a new machine that will give us the same old answers?" Although many of the timber›supply issues addressed by our predecessors can be addressed with the local›market model, important gains are promised. The model captures the entire timber economy within Oregon's borders and links Oregon to the outside world's demand for products and logs; the focus, therefore, is not just timber supply. As a corollary, the complementarity between public land›management plans and the market model allows users to comprehensively understand and display considerably more than the timber›supply consequences of resource-management choices. The promised gains require further work before we can declare them fulfilled; experience thus far, however, suggests that we are on the right track.

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Multi-Purpose Management of Forest Resources

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Abstract.--A framework for applying multicriterion decision-making techniques to the management of southwestern United States ponderosa pine forests is presented. The procedure consists of stochastic precipitation and temperature models as inputs into simulation models of forest products and decision-making routines that evaluate alternatives considering environmental consequences and recommensurate values.

It is well recognized that the United States Forest Service and, in some instance, other land management agencies are required by law to produce alternative forest management plans that provide for the multiple use and sustainability of goods and services that maximize long-term net public benefits in an environmentally sound manner.

The purpose of this paper, therefore, is to outline a methodology for evaluating and selecting a particular forest management plan that will best meet the desired objectives without undue stress on the environment. In formulating the problem in the proposed framework, consideration is given to a variety of silvicultural practices and/or cultural treatments that may be selected for a specific area. At the same time, it is recognized that most forest lands are not homogeneous in soils, topography, geology, vegetation, etc., such that a forest must be treated by a number of practices. Then, as the hydrologic regime transcends the entire watershed, a logical basis is provided for ascertaining the environmental implications of a management practice or treatment by analyzing the hydrologic outputs from a watershed.

FRAMEWORK

The proposed decision-making process for selecting the "best" management plan consists of (1) a time series of meteorologic inputs (primarily precipitation and temperature), (2) a set of models that simulate the outputs from a forest (e.g., water, timber, and forage), which includes the environmental consequences of management decisions, (3) the development of alternative plans, and (4) decision-making techniques for selecting the best alternative for meeting agreed-upon objectives.

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Simulation

Simulation has been used to represent the dynamic process for a wide variety of situations in forest management. In simulating large-scale forestry systems, key parameters and variables can be systematically varied to allow monitoring system performance under a range of conditions. A dynamic simulation model is a representation of such a system as it evolves in time. Thus, a stochastic approach, the result of simulation of both inputs to and outputs from the system, allows for consideration of a variable hydrologic regime, vegetative growth to take place and its hydrologic implications and for the implementation of management plans over time.

In this approach, a time series of daily precipitation amounts and temperatures are developed and used as inputs into deterministic forest, range, and watershed models to produce a synthetic record of hydrologic and environmental outputs. The use of synthetic records are suggested inasmuch as the historical record may not be long enough to include records of extreme events.

Multicriterion Decision Making

The management of forest resources is a complex process that may often involve attempting to meet competing or conflicting objectives. Furthermore, the assessment of certain values, such as aesthetic factors, either enhanced or diminished by a management decision, is often controversial as these values can not be readily quantified in economic terms.

The stimulus for using multicriterion decision-making techniques is essentially based on the position taken by the Forest Service in their scheme of management that requires alternative plans to be produced that provide for the multiple use and

sustained yield of goods and services from the National Forest system in a way that maximizes long-term net public benefits in an environmentally sound manner (U.S. Forest Service 1982). Thus, management appears to recognize that the ecological setting of natural resources in a forest ecosystem requires careful consideration of the physical, chemical, biological, and other relationships such as socio-economic and institutional, that may arise when one or more of these resources are artificially affected.

The use of multicriterion decision-making techniques for a forest system will be discussed later in this paper.

HYDROLOGIC SIMULATION

As with any system, inputs are transformed into outputs via some mechanism. In this case, hydrologic variables/primarily precipitation and temperature) are inputted into a watershed model to produce such outputs as water yield, sediment yield and water quality indices.

Meteorologic Inputs

To properly evaluate the impacts resulting from altering the hydrologic regime of a forest, a time series of meteorologic inputs are required of sufficient duration that extreme events or combination of events are considered. For example, problems of erosion are usually not caused by moderate storms, but from these that have a probability of occurring at least once every 50 or more years. It can make considerable difference in an economic evaluation if a storm has an exceedance probability of 0.02 or 0.002. Also, drought implications can be more severe from two consecutive moderately dry seasons than from one real dry season. Existing precipitation records may not always contain such a situation. A brief discussion follows on precipitation and temperature models.

Precipitation

Event-based precipitation models developed over the past 20 years at the University of Arizona, are the basis for developing a synthetic record of precipitation inputs into watershed, range, and other models (Duckstein et al. 1972, Duckstein et al. 1979, Fogel et al. 1974, Fogel and Duckstein 1982). First, the seasons (generally two, summer and winter) are separated based on meteorologic conditions as the short-duration, high-intensity, localized summer-type convective storms are markedly different from the winter frontal storms. These events are defined, and then Monte Carlo simulation is used to produce one likely time series or a number of equally-likely series of individual events. Using a synthetic time series based on the statistics of an existing record, tends to assure that extreme events are considered in the evaluation process.

Temperature

Daily temperature is modeled as a stochastic process using two elements, one deterministic and the other probabilistic. The first element is a simple harmonic function which describes the long-term daily means of maximum daily temperatures; this can be either a basic sine or cosine function. To account for the daily means and the many short-term cyclical patterns observed within any one year, a probabilistic component is incorporated. Since the current day's temperature is somewhat dependent on the prior day's temperature, some form of auto-correlation is required.

Daily temperatures are introduced into the snow accumulation and melt routines of watershed modeling and into the crop and range production models.

Hydrologic Outputs

A deterministic watershed model transforms a series of daily meteorologic inputs into a time series of outputs that include water yield and such environmental indicators as sediment yield and other water quality indices.

Water Yield

While no existing hydrologic model has universal appeal, some do exist that if properly calibrated and tested can give reasonable results. That is, they are sufficiently sensitive to determine consequences of land use changes and, most importantly, to silvicultural practices. Examples of general continuous watershed models are the Stanford Watershed Model (Crawford and Linsley 1966), the "Sacramento" or the National Weather Service-California Department of Water Resources Model (Burnash et al. 1973) and the USDA Hydrograph Laboratory Model (Holtan et al. 1975). These models require both precipitation and streamflow data for calibration in estimating a number of parameters.

In the case of ungaged watersheds, where snow-melt runoff is not considered, the most probable model choice will be one based on an USDA Soil Conservation Service procedure which has a computerized formulation (U.S. Soil Conservation Service 1983).

Where only augmented streamflows resulting from vegetation modification are required, an approach suggest by Ffolliott and Fogel (1986) may be used. In contrast to the above models, which uses daily precipitation to produce water yield on a daily basis, this approach uses seasonal or annual precipitation.

Environmental Indicators

Another class of hydrologic outputs include sediment yield, chemical loadings, and other water quality indices. These outputs are usually sub-routines to hydrologic models and as

such, they require additional parameter estimates and their outputs are often subject to question.

Forest Product Simulation

For this study, the forest resources that are simulated are water, herbage, and timber. The hydrologic simulation, presented in the previous section, becomes an essential factor in the simulation of herbage production. Timber growth and yield models, however, do not require daily inputs of precipitation and temperature.

Herbage Production

Prediction models of herbage production are available that use daily inputs of meteorologic variables and estimates of site parameters. Examples are the model developed at Colorado State University (Gilbert 1976) and the one developed by the Agricultural Research Service of the USDA (Wight and Skiles 1987). Both models include a forecasting procedure that utilizes either historic or synthetic data, principally precipitation and temperature.

Timber

Harvest flows represent the timber volumes removed over time from existing timber inventories or stock supplies of stumpage. Modeling of these flows consists of two components, land allocation and timber growth and yield, and involves the dynamic interrelationships between biological and economic forces.

One class of models often used are the variable density growth and yield models, which are constructed to provide both growth and yields corresponding to different stand densities. Such models are of great value in contributing to the ability to represent potential results of different silvicultural management alternatives (Alig et al. 1984). Such models have been constructed at the University of Arizona and elsewhere.

Multicriterion Decision Making Applied To Forest Management

The purpose of this section is to discuss the applicability of multicriterion decision-making (MCDM) techniques to a forest resources management situation in terms of problem formulation to include the development of a "typical" set of objectives, specifications, and criteria and some of techniques that may be used.

Problem Formulation

Forests possess numerous resources and other support elements which may or may not be readily quantified. A management scheme for such an area can be described using noncommensurate objective and data consisting of cardinal, interval, and ordinal information. Such problems need to be presented in a format suitable for MCDM analyses.

Objectives

According to the U.S. Forest Service Multipurpose Forest Management Guidelines (U.S. Forest Service 1982), there are eight goals and four support elements in a National Forest management plan.

The goals involve:

1. Water yield
2. Timber production
3. Recreation
4. Wilderness
5. Wildlife and fish
6. Range
7. Minerals
8. Human and community development

The following are considered as support elements because they are essential for the development and appropriate management of natural resources, so that the above goals can be realized in specified manner.

1. Land
2. Soil
3. Facilities
4. Protection

To evaluate the relative merits of a number of alternative plans using MCDM procedures initially, the problem should be specified in terms of objectives, specifications, criteria, and criterion scales. An example of this is shown in table 1.

Evaluation Matrix

The next step in the problem formulation is to develop an evaluation matrix, which is an array of outputs based on various criteria for a number of selected alternatives. Table 2 presents an example of this array. The criterion weights in this array are selected to reflect the decision-maker's preference among the given set of criteria. A range of scales may be used to measure the degree of discomfort the decision maker may experience in moving from the "best" to the worst scale point in one criterion compared with a similar operation on another.

DECISION-MAKING TECHNIQUES

The most well-known decision-making technique is without a doubt goal programming (Cohon 1978). Initially it was

Table 1.--Objectives, specifications, criteria, and criterion scales.

Objectives	Specifications	Criteria	Criterion scales
Increase water yield	Increased flow; Water quality	Increased water yield; Sediment yield	Volume (AF/Ac); Volume (tons/ac)
Improve range condition	Livestock and wildlife forage; Habitat range	Forage; Production; Habitat status; Range condition	Lbs/Ac; Ordinal;* Ordinal; Ordinal
Develop recreation	Recreational (various kinds); Preservation of existing facilities;	Aesthetics Level of preserving existing facilities	Scenic value Ordinal
	Creation of new opportunities (hunting, roads, camping site, etc.)	Possibility of creating new facilities	Ordinal
Maximize commercial benefits	Timber; Livestock;	Timber sale; Livestock value;	&/Acre &/Acre
	Firewood, fence post and stumpage.	Firewood and fence post	Ordinal
	Streamflow;	Water yield	&/Acre
Optimize resources utilization	Operational cost; Maintenance cost; System operability	Total cost Ease of operation	&/Acre Ordinal

**Ordinal implies a 5-point qualitative scale ranging from a = best to e = worst.*

employed almost exclusively in the private sector, but of late, it has been used most extensively in natural resource management problems (Dykstra 1984). This section will present first description of three other types of techniques, two of which are the outranking type as exemplified by ELECTRE I and II (Duckstein and Gershon 1983) and the distance-based technique of compromise programming (Zeleny 1982). A more detailed description of these two methods as applied to forest management is found in Tecle et al. (1987). Another technique is one that is called the Evaluation and Sensitivity Analysis Program (ESAP), which is a general-purpose software aid to decision making that can be adapted for use in many disciplines (Mumpower and Bollacker 1981).

ELECTRE I and II

These outranking techniques have been developed to determine a preference ordering among a discrete set of alternatives with respect to a set of criteria by pairwise comparisons of the alternatives. Important elements in these two alternative actions m and n is a weighted measure of the number of criteria for which m and n is a preferred to n. The discordance index, on the other hand, represents the maximum discomfort one experiences when confronted with criteria for which m is not preferred to n.

In addition to the concordance and discordance equations, the ELECTRE II methodology uses a strong and weak ranking relationships among the alternatives in order to bring about a

Table 2.--Evaluation matrix (criteria versus alternatives).

Criteria	Wt.	Scale	Alternatives 1	2	3	4	5	6
1. Streamflow (AF/Acre)	9	200	0.509	0.673	0.650	0.480	0.710	0.780
2. Sediment yield (in tons/acre)	7	150	0.030	6.020	0.360	0.040	0.050	0.160
3. Forage prod. (lbs/acre)	8	180	329	833	126	325	460	490
4. Range condition	7	150	B	D	A	A	B	C
5. Habitat condition	8	100	C	E	B	A	B	D
6. Preservation of existing facilities	5	100	A	E	B	B	D	D
7. Creation of new facilities	6	75	E	B	C	C	B	B
8. Aesthetics (scenic value)	8	150	2.100	1.200	2.500	2.000	1.850	1.420
9. Timber prod. (current $/AC)	8	200	1644	16	1777	3147	3225	3273
10. Livestock prod. (current $/AC)	6	150	0.548	2.010	0.200	1.120	2.400	0.940
11. Firewood and fence post	4	80	C	E	B	B	B	D
12. Water yield (current $/AC)	8	150	10.17	13.45	13.00	9.530	14.20	15.52
13. Total cost ($/AC)	7	150	0.000	160.0	54.00	89.00	134.0	118.0
14. Ease of operation	4	120	A	B	C	D	D	C

Note: wt. = criterion weight.

complete preference ordering of the alternatives. The strong and weak outrankings are then defined by pairing individual levels from each index. One alternative strongly outranks another when a pair consists of high concordance and an average discordance threshold values, or have a pair with an average concordance and a low discordance values. On the other hand, an alternative weakly outranks another when either the concordance and discordance pair of threshold levels provided are both low, or both are average. Once the strong and weak outranking relationships are constructed, a complete ordering of the nondominated set of alternatives may be obtained.

Compromise Programming

This technique is designed to identify solutions which are closest to an ideal point by some distance measure (Zeleny 1982). In a discrete setting, the ideal solution is defined as the vector of best values selected from a quantified evaluation matrix. The vector of worst values represents the minimum objective function values, these values are valuable in determining the degree of closeness of an alternative to the ideal solution.

EVALUATION AND SENSITIVITY ANALYSIS PROGRAM

ESAP can analyze a large number of variables (objectives) which are specified and organized by the user into a hierarchy or "tree." The user provides a goal for each variable and weight (importance) for each goal. The intellectual roots of ESAP lie in the field of decision analysis generally and in multiattribute utility theory in particular.

After each variable is assigned a weight, the user specifies values for each variable or factor, usually in terms of maximum and minimum levels. These levels indicate the range of available data or outputs from simulation models. Where no specific data are available, the values are based on an ordinal scale, and since they are subjective, the user can indicate an uncertainty in their value by specifying a range.

Then for each factor, a utility function translates these values into a common term, utility, which allows the user to assess the performance of each alternative course of action. This approach to selecting the "best" alternative for forest management has an appeal because it is straightforward in approach.

DISCUSSION AND CONCLUSIONS

Most if not all of the simulation models and decision-making techniques presented herein have been used in a variety of packages. In some instances, problems have developed such as in parameter estimation and in reliability, dependability, and reasonableness of results. Nevertheless, the approach is sound and with newer and better models and techniques and with more data, the objectives can be overcome. Thus, a general conclusion of this effort is that the use of simulation models as inputs into multicriterion decision-making techniques is a viable approach for managing forest resources.

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Multilevel Planning in a Spreadsheet Environment

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Abstract.--This paper describes a multilevel approach to planning and budgeting within the spreadsheet environment of the Forest Service. Spreadsheets are arranged in a pyramidal and hierarchical fashion which defines the flows of information from one level of the organization to the next. Experience gained from applying this approach to the Southwestern Region is presented. The spreadsheet approach to multilevel planning is compared and contrasted with earlier approaches which advocated the use of mathematical programming to accomplish the same objective.

Introduction--Multilevel Planning in the Southwestern Region

When viewed from the perspectives of local, regional, and national planning, the Forest Service is a hierarchical organization. A typical depiction of the participants in the vertical hierarchy follows:

1. President, Congress, and the Judiciary System
2. Secretary of Agriculture
3. Chief of the Forest Service
4. Regional Forester
5. Forest Supervisors
6. District Rangers

The topic of the next paper in this session is hierarchical resource allocation mechanisms. My paper describes a spreadsheet mechanism for resource allocation in a hierarchical organization.

The preceding paper dealt with another aspect of managing the National Forests--the fact that we are involved in multiple use management. The participants in this vertical hierarchy are engaged in one or more aspects of managing timber, soil, water, air, range, wildlife, recreation, and cultural resources; protecting these resources from fires, insects, diseases, and pollution; and utilizing these resources with improved production, marketing, engineering, and citizen participation.

All National Forests in the Southwestern Region will have published final Forest Plans this year. The standards and guidelines in these Plans reflect decisions about how the Forests will be managed during the life of the Plan--a 10- to 15-year period. All actions taken within that period of time are directed at implementing the Plans. An evaluation or feedback process is included to indicate whether corrections and revisions of Plans and actions are needed. At the project level, an IRM (integrated resource management) approach has been adopted for implementing Forest Plans. This is a thirteen-step process which represents a horizontal hierarchy or multiple-step implementation process through time. The thirteen IRM steps are:

1. review the Forest Plan,
2. develop the project concept,
3. conduct extensive reconnaissance,
4. prepare a feasibility report,
5. update the Forest 10-year implementation schedule,
6. conduct intensive reconnaissance, survey, or design,
7. generate and compare alternatives,
8. alternative selection,
9. prepare NEPA documentation,
10. create a project record,
11. prepare a project action plan,
12. field implementation, and
13. monitoring and evaluation.

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In the above IRM process, the multilevel spreadsheet is utilized in steps 5 and 13. In the Southwestern Regional Office, the multilevel spreadsheet is used for the following activities:

1. preparing annual budget proposals,
2. issuing budget allocations,
3. evaluating partial level budgets,
4. tracking the results of monitoring,
5. conducting general management program, and activity reviews,
6. making the required 5-year Forest Plan implementation review,
7. evaluating the need to amend or revise Forest Plans,
8. communicating with the public,
9. consolidating data from other information systems,
10. establishing project priorities,
11. tracking accomplishments,
12. adjusting skills and organization,
13. defining information needs,
14. preparing the RPA Assessment and Program,
15. responding to Congressional requests for budget line item information by Forest and Region, and
16. conducting the performance appraisals of Forest Supervisors and Regional Staff Directors.

Why Use Spreadsheets Instead of Mathematical Programming?

Nationally, the Forest Service is a large organization with approximately 800 offices and 35,000 employees. As the preceding discussion indicates, our Region is operating in a multiple level, multiple purpose, multiresource, multiple use, multiyear environment that has both vertical and horizontal hierarchies and processes. We need a fast, cheap, simple, efficient, and effective means of acquiring, analyzing, interpreting, displaying, and transmitting information to planners and decisionmakers at each level of the organization. We need uniform and consistent information which can be used in all related processes--data which is credible and comprehensible to both ourselves and to our interested publics. The software utilized for processing this information should be compatible with existing office automation software utilized throughout the National Forest System. The hardware requirements for processing this information should be the existing network of distributed processing facilities available throughout the organization. A comparison of the pros and cons of a spreadsheet approach with a mathematical modeling approach using any and all of the above criteria indicated that the spreadsheet concept was the most appropriate technology.

Of supreme importance in implementing multilevel modeling is the human relations aspect of the analytical process. Too often, analysts are overly concerned with the mechanics and theoretical niceties of our analytical systems; see Hof and Pickens (1986) for example. However, the effectiveness of a system depends on whether the managers it affects understand it, accept it, and use it. Rightly or wrongly, the time-consuming, costly, "black box" experience associated with our large-scale mathematical programming endeavors in the past has engendered a fear of paralysis from analysis which is associated with sophisticated models. In contrast, a spreadsheet procedure using hardware which is within an arm's reach of each Forest Service employee using familiar software becomes fast, cheap, and accessible.

Meetings, such as the one that we are attending today, often are devoted to techniques which can only be utilized by the top percentile of analysts and computer acrobats in the organization. However, to be effective in a large complex organization, a technique may need to be geared to the lowest common denominator of computer literacy, hardware and software in that organization; a spreadsheet approach comes very close to hitting this target.

One of the major arguments against a spreadsheet approach is that it is too simple. (Note: this is one of the main arguments for a spreadsheet approach, as well.) Simply aggregating Forest Plans to a Regional level, or proportionately spreading Regional targets and budgets to a Forest level will not result in the most efficient output mix to be produced or the most efficient means of producing it. While this is true, efficiency analyses have already played an important role in the development of Forest Plans. Spreadsheets don't have to solve all of our analytical needs. Other analytical systems which focus on efficiency analysis, such as network analysis models, can be used in conjunction with spreadsheets in the Plan implementation process.

Criteria other than efficiency (for example, equity and effectiveness) play a major role in Plan implementation (Weisz and Stewart 1987). Spreadsheets are a good enough technology for handling these other criteria.

The mathematical programming approach in a multilevel organizational environment is most consistent with a centralized approach to planning and decision-making which places maximum constraints and the minimum amount of freedom on lower levels of the organization. In contrast, the spreadsheet approach in a multilevel organization is more congruent with a decentralized approach to management which provides minimum constraints and maximum freedom to the lower levels of the organization. A major benefit of the decentralized approach is that Forest Supervisors and District Rangers have the best information concerning local conditions and therefore are better able to make site specific resource decisions than those who are employed in the Regional Office. Lower level line officers gain valuable management experience by being able to make inde-

pendent decisions. Trusting lower level managers and giving them more independence results in a more enjoyable job environment and a higher level of morale at the National Forest level. Finally, as Project Spirit has demonstrated, if lower level managers are given fewer constraints, they may be more productive than if they are operating in a more centralized bureaucracy.

Other arguments against overly stressing the advantages of efficient analytical techniques are based on the very nature of our organization. We do not have a single bottom line profit criterion which can be maximized in the most efficient manner. Our goals and objectives are less clear; we operate in fuzzy decision environments. Only one of our multiple purposes is to operate efficiently. Archaeologists, biologists, and other professionals who are employed with the Agency, did not enter this line of work to maximize profit. Our diverse publics have a variety of goals and objectives which are difficult to consolidate into one index of efficiency.

A basic assumption of most mathematical modeling techniques is that relationships between inputs and outputs are certain; however, in the real world, measurements are difficult and data is often lacking. Our analytical techniques should not be anymore sophisticated than the data which they utilize.

In summary, a cost-benefit approach was applied to comparing the spreadsheet procedure with the mathematical programming approach to hierarchical multilevel modeling. We concluded that the spreadsheet approach was both the least-cost approach and the most effective alternative for meeting most of our criteria.

How Does the Hierarchical Spreadsheet Work?

Our basic assumption is that Forest Plan implementation is the focus of planning and decision-making at all levels of our organization. However, Forest Plans are mostly programmatic and guide expected accomplishments for 10 to 15 years. While Plans provide some scheduling information, little site specific and time specific information is provided. For example, Plans may contain proposals for a series of planned timber sales, nomination of a national historic trail, construction of recreation water and sanitation facilities, off-road vehicle closures, visual resource inventories, etc. However, many questions are not specifically answered in the Plan. For example, when during the planning period will these projects be scheduled? When will funds be requested? When will funds be received? How close to a full level of funding will be received? How will we keep track of our accomplishment? Which project should be highest priority? Can joint inventories be accomplished? Can joint projects be designed? Are projects in conflict with each other? Can projects be scheduled for greater efficiency? The 10-year implementation schedule developed on each Forest provides basic information for answering some of these questions.

Specific annual schedules must be prepared that mesh with the annual budget process and site specific project analysis.

THE NATIONAL FOREST PLAN IMPLEMENTATION AND MONITORING SPREADSHEET
DATE XX/XX/XX

FUND CODE	ACTIVITY CODE	COSTS IN M$	FY'87	'88	...	'96
NFAF	FOREST	FIRE MGMNT				
		(item description)	..	..		..
		TOTAL M$	..	..		..
.	.	.	.	.		.
.	.	.	.	.		.
.	.	.	.	.		.

Continued for each of 43 standard cost categories.

NFSW	FW22	WATERSHED IMPROVEMENT ACRES				
		(item description)	..	..		..
		TOTAL WATERSHED IMPV ACRES	..	..		..
.	.	.	.	.		.
.	.	.	.	.		.
.	.	.	.	.		.

Continued for 50 items required by the Chief.

Continued for 24 tracking items required by the Regional Forester for land ethics and regional issues.

Continued for any items desired by Forest Supervisor.

SUMMARY STATISTICS FOR REPORTING TO THE REGIONAL OFFICE

The TOTAL lines above are displayed here and reported to the Regional Office. While the Forest at its discretion can track individual items by additional detail such as by project, analysis area, management area, or Ranger District, the summary statistics portion of the spreadsheet is the only portion that is mailed to the Regional Office. This provides our total information needs for LMP monitoring, program development, budgeting, RPA, etc. We do not intend to go back to the Forest for additional information. Some right-hand-side statistics appear to the right of the '97 column which indicate the percent of planned goals which have been attained to date.

Figure 1.–Simplified schematic diagram of a forest's spreadsheet.

Progress toward Plan accomplishment must be tracked and evaluated. Scheduling changes must be recorded and impacts of budget deviations must be displayed. The need to change the Plan must be analyzed. The public must be informed.

Plan implementation schedules will be the basis for prioritizing work. They also will be the basis for eliminating lower level priorities.

An abbreviated schematic diagram of the implementation schedule is illustrated in figure 1. The FUND and ACTIVITY code columns on the left are standard NIR (National Information Requirement) codes which are used throughout the organization. Uniform and consistent codes are needed to avoid creating a Bureaucratic Tower of Babel in a multilevel organization.

The potential of goal programming as a decision support system was discussed earlier in this symposium by Larry Davis. A related topic, goal scheduling, is accomplished with the implementation spreadsheets. Goal scheduling has several components. They include:

1. reviewing the Plan,
2. setting goals,
3. writing out the goals,
4. charting progress in attaining the goals, and
5. evaluating results to date.

The exercise of scheduling out the Forest Plan has increased understanding of the Plan and commitment to it.

The individual Forest Plan implementation spreadsheet is a simple and effective tool. It will do more than anything else to facilitate understanding of the Plans by the public. The implementation schedule and the graphs which accompany it visually display the entire Forest Plan, and track accomplishment toward meeting planned goals and objectives.

Continued citizen participation is one of the critical aspects of monitoring Forest Plans. We will continue to seek public participation in Forest Plan implementation. The implementation schedule will be a primary tool to show the public what we have accomplished to date, and what remains to be accomplished during the Plan period.

It is important that the public as well as our managers know how successful our management programs are. The public can help us design better ways to correct problems if we begin to drift away from implementing our Forest Plans. We will develop a layman's guide to Forest Plan implementation which defines the implementation strategy in a concise and understandable way.

This will be published each year as an "annual report to our shareholders." This will summarize the results of Forest Plan implementation. It will show our normal accomplishments such as timber produced, forage grazed, etc. However, the unique thing about our report is that it will emphasize qualitative aspects of caring for the land--those items which are associated with land ethics. For example, figure 2 illustrates what we expect to happen to satisfactory watershed condition acres over the life of this first generation of Forest Plans. The information provided on each land ethic item will indicate

1. what is planned for the Plan period,
2. what has been accomplished to date, and
3. what remains to be accomplished over the remaining life of the Plan.

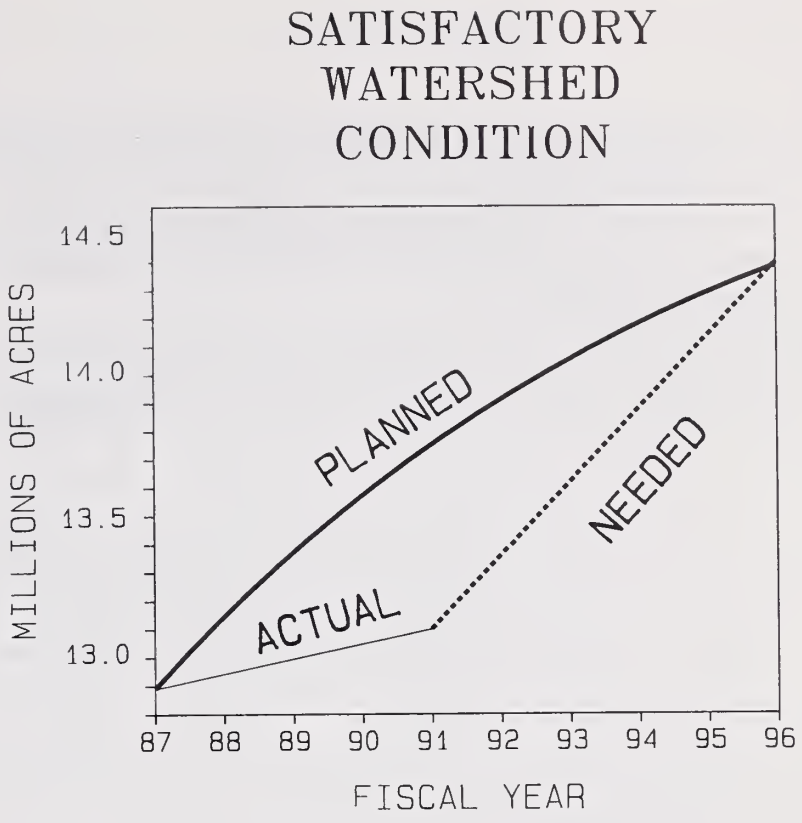


Figure 2.--An example of a land ethics graph.

Forest Plans delegate a large degree of discretion and responsibility to the Forest Supervisors for Plan implementation. The Regional Office role will shift appropriately from control to emphasize quality review. The spreadsheets will facilitate this move to a more decentralized organization.

The spreadsheets are living documents. They are constantly being updated at the Forest level to reflect new knowledge gained from monitoring, deviations between the planned schedule and accomplishments, as well as amendments and revisions to Forest Plans. At least twice a year, the Regional Office takes a snapshot of each Forest's spreadsheets in order to put together a regional photo album of the state of our forests at a given point in time. This constant update feature allows us to monitor the results of Forest Plan implementation, develop program proposals to submit to the Washington Office, allocate budgets and targets to the Forests, etc.

In contrast with our experience, a more sophisticated hierarchical analytical system either would not have been implemented in the first place, or would have been put on the shelf within a couple months. By using a simple, down-to-earth, user-friendly system, we have a hierarchical modeling system which truly can say, "I have been used."

In the introduction to this paper, the sixteen uses of the spreadsheet by Regional Office personnel were listed. Most of these applications have taken place in the past couple of months. We expect this simple frame of reference (or something similar) for Forest Plan implementation to continue to be used in the years ahead.

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Acknowledgments

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Design of a Resource Allocation Mechanism for Multiple Use Forest Planning

Gonzalo L. Paredes V.[1]

Abstract.--A method for implementing a systematic forest planning process is presented. The features that make hierarchical decomposition are explained. Recent developments in economic planning and management theory that should be incorporated into the design in order to overcome the shortcomings of the current planning experience are described.

The practice of planning in forest organizations, public, or private has become the focus of attention in recent years as the forest land base decreases and society values multiple outputs from the forest. It is also becoming apparent that the forest sciences, mainly forest economics and management, have not yet developed an appropriate and generalized framework for successful implementation in actual institutions. Where multiple-use forest planning and economic efficiency are institutionally requested, the modeling approaches currently undertaken have either increased problem complexity to levels beyond the comprehension of the managers, the public, and even the modelers themselves; or simplified it to levels where it no longer allows for efficient allocation decisions.

The above situation is evident in public agencies where timber, recreation, wildlife, water, and other nonmarket commodities have to be accounted for in the planning process. But in large private corporations the nonmarket concerns are often replaced by other pseudo-commodities such as cash flows, market share, financial ratios, and other externalities. The analogies are in many cases straightforward, thus the concepts discussed in this paper, although related to planning in a public agency, can be extended to private firms.

The purpose of this paper is to provide a theoretically sound framework to analyze planning issues recently brought up by the current experience of the USDA Forest Service, where an attempt to utilize a mathematical programming technique as a tool in the planning process has produced less than satisfactory results.

The concepts presented in the paper strongly rely on the use of duality theory embedded in the mathematical programming techniques commonly used in forest planning. As illustrated in Paredes and Brodie (1988a), the practice of forest planning can not neglect the concepts and the economic rationale embedded in mathematical programming commonly used in forest planning. The analysis of key forest policy issues can be illuminated if basic duality rules are observed. Also the linkage between stand- and forest-level planning can be established through duality concepts (Paredes and Brodie 1988b).

Next, we illustrate the characteristics that make multiple-use forest planning a large-scale task, and presents the main criticism to the currently, primal approach to forest planning implemented in many public and private forestry agencies.

Finally, it is necessary to describe some of the concepts from economic planning theory that have been absent in forest planning literature. During the last two decades interesting and practical results have been obtained in the design of resource allocation mechanisms to improve the economic efficiency of existing ones. It is self-evident that the implementation of a planning process will normally require more than the simple choice of a mathematical device in order to produce satisfactory results.

The fourth section describes a short-run resource allocation model for multiple-use forestry at a regional level. It describes a process within which local managers and regional managers interact with a language of production targets and shadow prices in an iterative process that, once implemented, can be conducted continuously. A general description on how the model addresses and solves the managerial efficiency problems currently present in planning processes is also given.

The Planning for Multiple Use of Forest Lands

The performance of a forest planning process has been traditionally viewed as dependent on, or conditioned by, the

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analytical model utilized. In describing analytical requirements for multiple-use forest planning Teeguarden (1987) points out that some of the "generic characteristics of the ideal analytical model...[are] the following key structural capabilities" (p.20): (1) simultaneous multi-resource land allocation, activity scheduling, and prescription selection analysis; (2) analysis of both spatial and temporal allocation problems, including the effect of policy constraints; (3) establishment and analysis of vertical linkages between forest, regional, and national levels; (4) establishment and analysis of horizontal linkages to other national forests and the private sector in a region; (5) economic efficiency analysis; and (6) economic and social impact analysis.

With all these requirements, in addition to others, multiple-use forest planning becomes a large-scale and complex task.

Simultaneous consideration of spatial and temporal relationships, externalities of timber production and vegetation manipulation, and production of non-market goods and services raises the complexity level beyond the limits of any single technique. Forestry literature reveals that the approach generally utilized to deal with these aspects has been to break down the problem in the sense that one requirement is addressed at a time. Then, the modeling technique is enlarged to account for that aspect, and finally its mathematical properties are studied in order to derive a numerical procedure that overcomes the computational burden of the previous enlargement.

Modeling in Forest Planning

Modeling efforts have been largely dominated by their focus on the dynamic nature of forest systems production. Issues such as forest regulation, long run sustained yield, and non-declining flow of timber are important and traditional concepts inherited from nineteenth century forestry in Europe. Foresters have to deal with them in forest modeling and planning processes. A survey by Reed (1986) presents many of the relevant approaches to account for the time dimension of forest planning. When the initial state of the forest does not present the equilibrium conditions for maximum sustained yield, binary search, the maximum principle, and linear programming have demonstrated their suitability to deal with the dynamic aspects of large scale forest planning.

Well known examples of linear dynamic models for forest planning are the works by Johnson and Scheurman (1977), Navon (1971), and a modeling scheme recently proposed by Reed and Errico (1986). The incorporation of time on forest resource allocation has an explosive effect on problem size. Without aggregation of time periods, problems soon become intractable within a linear programming approach as the number of stands or time periods increases. However, their linear formulation presents a well-defined staircase structure suggesting the use of decomposition techniques. The works by Berck and Bible (1984), Caswell and Rao (1974), Ericksson (1983), Hoganson and Rose (1984), Liittschwager and Tcheng (1967), Nazareth (1980), and Williams (1976) are some of the efforts along the lines of the Dantzig and Wolfe (1960) technique, to overcome the computational burden of large-scale harvest scheduling problems. Their focus has been on the computational aspects of using this technique when forest planning is enhanced with respect to the time dimension.

Forest modeling efforts were enhanced in the early 70's when it was realized that, to solve for the best use of forest land, not only a dynamic problem had to be solved, but also a spatial location problem in order to obtain meaningful and implementable land use decisions.

The first aspects to be identified as closely related to spatial dimensionality were those on transportation activities.

By observing that usually a slight increase in timber harvest costs, because of a shift in stand location, can be more than offset by reduction in transportation costs, Kirby (1973) initiated a modeling effort that demonstrated the advantages of simultaneously analyzing wildland resource management projects and their required road network. Kirby introduced a mixed integer programming (MIP) formulation, named Integrated Resource Planning Model (IRPM), to solve for an optimal performance of land use projects less transportation costs (including road construction) subject to management constraints and to temporal and spatial dependence between projects and access roads. Until then the U.S. Forest Service and private industries had been solving separate transportation plans for each land use project.

Global network analysis for all projects with shared access became a promising modeling approach for meaningful forest planning. The interest later tended to dissipate when researchers and practitioners realized that no algorithm with polynomially bounded execution time could be found to solve for the concave programming problem resulting from MIP models. The approach is therefore used in small size, short-run, planning problems.

In response to the proposal of MIP models for use in forest planning and because of their high computational requirements, planners in the U.S. Forest Service have incorporated very much the same features of Kirby's model into the LP-based FORPLAN system (Iverson and Alston 1986). Since the simplex code assumes continuous linearity on activities relationships, users have adopted a heuristic approach by rounding-off and/or redefining the projects that should correspond to integer variables but are treated as linear ones in the FORPLAN model. As is well known, this simplest heuristic to obtain integer solutions from an LP relaxation may result in large deviations from the true optimum to the MIP problem. Sessions (1985) and Weintraub (1978) implemented more elaborate heuristics.

It has been later demonstrated that the MIP approach can also be tailored to solve for other spatial aspects of multiple use land planning (Kirby et al. 1986), such as recreational uses, streamflows sedimentation, and wildlife habitats.

An alternative method to account for spatial relationships between stands has been developed by Bowes and Krutilla (1985) using dynamic programming to solve for multiple stands management with timber and non-market outputs.

The solution methods outlined above have all a common ingredient: their developers have attempted to solve as much as they can while using a single optimization technique. Furthermore, forest planning has been viewed as a single-level exercise as if every aspect of the decision process could be adequately addressed through a unique model. The results are formulations that tax either planning staff comprehension or computing capabilities. It is also now becoming clear that an undesired by-product of a single-level approach has been its inability to model the linkage to other agencies and to other decision making levels within the institution.

In light of the problems of practical forest planning, the idea of partitioning the planning process has recently grown up among forest managers. One of the catalytic elements has been the current experience of the planning process as conducted in the U.S. Forest Service in implementing the U.S. National Forest Management Act. A "rational-comprehensive multiple-use planning of the National Forest system" (Teeguarden 1987) to maximize a vaguely defined concept of "net public benefit" has been mandated to the agency. Then, the Forest Service has relied, as its "main analytical tool" (Russell 1987) on a computer code that permits formatting of raw data into a matrix input for a commercial Linear Programming code to solve the problem. Then this code (FORPLAN) tabulates and summarizes results (Johnson et al. 1986). The capability to automatically generate a system of linear equations that could then be processed and solved by the simplex algorithm has fascinated planners in the agency. As a result discussions on the planning process invariably shift into the analysis of the matrix generator/report writer, instead of the process itself.

The issue of coordination of the planning process with other public and private resource allocations has been recently raised as a major source of criticism in the National Forest planning process. It is often observed that the planning process does not link planning at the forest level, the Resource Planning Act (RPA) program, and the annual Budget process. As illustrated by Beuter and Iverson (1987) "the planning process is done in a vacuum" (p. 92).

The planning process has been also characterized as having the effect of shifting "power upward in the classically decentralized Forest Service...(thus limiting) on-the-ground testing of alternative analytical approaches to the forest planning problem" (Binkley 1987, p. 101). Hierarchical, or multi-level planning, is claimed as a necessary approach also by Dykstra (1987). Also Beuter (1984) and O'Toole (1987) have argued in favor of implementing a somehow decentralized management of land units in a "business-like" fashion.

Few contributions are found in forest literature on analytical models to address either decentralization or inter- and intra-institutional linkages. The economic ideas embedded in the decomposition method of Dantzig and Wolfe (1960) provide a solid analytical framework to managerial decentralization and give a protocol of messages to be implemented in hierarchically dependent management units to achieve optimal allocation decisions (Baumol and Fabian 1964). However, of the works utilizing the method, only Williams (1976) seems to capture the idea of the Dantzig and Wolfe routine and provides an interesting, but sketchy, description of decomposition as applied to an idealized hierarchical decision process in a public forest agency.

As an attempt to overcome the lack of coordination between regional and forest levels, Hof and Pickens (1987) propose a two-level model where the upper level solves an integer programming problem with discrete activities, each representing the choice of management plans developed by the local planning units.

This model is conceived as a non-iterative process that would allow the planning authority (the U.S. Forest Service) to overcome the inexistence of "an elaborate communication network and coordinating authority" (p. 247), and the difficulties of concurrent operation of the planning process at lower-level units.

Navon and Weintraub (1986) suggest also a heuristic to elaborate supply alternatives for "a few neighborhoods" in the decision or policy space of the wildland enterprise (p. 354). The procedure involves only one iteration between central authority and unit managers. These submit only one set of discrete proposals, covering all scenarios, to the center. Then returned back a message describing their production plan is returned back. It is not clear, however, how the center formulates constraints for the global integer program, and how these models are interpreted in terms of their economic efficiency. It is convenient to recall that the "nonlinear outputs and inputs" which are dealt with in steps 3 and 4 are typically those representing public goods and externalities of multiple-use forest management. The economic interpretation of such an integer program could yield meaningless prices for non-market commodities.

By implementing management plans selected from among discrete options it becomes extremely difficult to adjust the operations whenever the institution detects wide environmental fluctuations or actual variations in the values for parameters of the model. This can be illustrated by considering, for instance, a situation where the global IP calls for a recreation-oriented plan at unit A, and for timber specialization in unit B. An observed small change in constraint level of the global IP, allowing for a reduction in the minimum level of recreation requested, may translate into a dramatic shift to a discrete choice of reduced recreation in unit B, after the initial investments for a timber oriented plan have been undertaken. This undesired situation can be obviously overcome if enough discrete choices are included so that a "smooth" transition is allowed. The tradeoff in this case would be a further increase in size of the, already large, integer programming problem.

In terms of message exchanges, the procedure requires massive data transmitted between the center and the units, and forces the center to solve two large-scale problems.

Partitioning of the forest planning problem has also been attempted in the planning practice of public institutions. Mitchell et al. (1987) describe a procedure that sequentially solves: (1) a one-period "steady state" model to address spatial manage-

ment issues; (2) a "harvest scheduling" model to analyze the dynamic characteristics of the timber harvest flow; and (3) a "final model" where activities are input according to selections made in the previous steps and modifications by operations personnel. The implementation of this procedure allows a heuristic reduction in the number of activities to be considered in the final planning model.

The planning process is still centralized at the forest level; however, it allows for certain involvement of the lower decision making level. In general, this procedure represents one of the many attempts that can be found in the practice of forest planning in order to break down the problem to actual comprehension levels.

As observed from the multi-stage modeling approaches discussed above, the driving concern in their development has been the search for computationally feasible methods for a large-scale problem. The limitations arise as a result of including, at the same resolution level, decision variables and parameters that correspond to different types of management participation. Reliance on a single mathematical programming method, without exploiting the advantages of specialized techniques, also characterizes the reported planning procedures.

This mindset has been pervasive in forest planning, and is well reflected throughout the experience of the U.S. Forest Service in implementing a "rational-comprehensive multiple-use planning of the National Forest system" (Teeguarden 1987, p. 20) to maximize a non-defined Net Public Benefit.

In failing to analytically account for many of the "key structural capabilities" enumerated early in this section, forest economists often rely on the literal wording of the relevant legal mandates, or on the properties of the analytical tool readily available. Teeguarden (1987), for instance, points out that "cumulative effects within a forest and across different forests within a region are not explicitly mentioned in NFMA or the Regulations" (p. 21), as if these were a recent issue not already revealed by, or implicit in, the overriding mandate of economic efficiency or maximization of "net public benefit," an ambiguous name for "social welfare."

With respect to reliance on the available analytical tool, the common belief is that with "the selection of FORPLAN as the primary analysis tool...the National Forests chose the pursuit of economic efficiency in their forest planning model over the detailed simulation of environmental effects" (Johnson 1987, p. 46). Economic efficiency is, however, granted by market equilibrium and welfare allocations beyond the use of any generic mathematical programming technique.

As illustrated in the previous paragraphs, the recent practice of forest economics and planning have been confounded by a number of policy issues and societal concerns on the management of public forest lands. Mathematical programming and computers have often been viewed as salvation devices and currently many state their hope on even more computing power or faster techniques. Instead, it is proposed here that the practice of forest planning could first recast some of the recent developments in management and economic theory. The next Section describes some of them.

A Strategic Allocation Model for a Forest Region

In multiple-use land management the need for a decentralized, hierarchical approach seems to be unquestioned because of the technical, ecological, and economic characteristics of the forest ecosystem production process. The issue is again raised now that the U.S. Forest Service has extensively implemented an uncoordinated, primal, centralized, and single-level planning process.

The relevant questions are: how to define the levels of control within an organization; how many are necessary, and how are they linked? A proposition for spatial hierarchies--nation, region, forest, and district--would be necessarily restrictive if a single planning horizon were attached to each level. Temporal hierarchy must also be defined at each level; at a national level, for example, budget allocations are conducted on a yearly basis, while another decision making process allocates long-term research and development projects.

Multi-level, multi-type decompositions of large-scale systems, formalized since the early 70's in systems engineering (Haimes 1982), result in multifarious subsystems that can be identified as being potentially viable or economically efficient (Beer 1979).

Having the above in mind, the following discussion on a forest resource allocation process focuses on a short-run regional economy. Short-run is here understood as the period of time where major investments relevant to a regional level are assumed as given. Normally a period of 5 years is considered appropriate.

Inherent in the design of a resource allocation process is the problem of representing society's preferences among alternative states of the economy, so that the problem can be stated as finding the most preferred feasible state. Usually societal preferences for public forest management are vaguely presented with expressions as "maximum social benefit" or "maximum net public benefit" without explicitly mentioning, but relying upon, some measures of economic efficiency and equity.

For a meaningful construction of an objective function representing societal preferences it is necessary to rely on the concept of tradeoffs between variables. The evaluation of these is greatly simplified if the objective function can be assumed to be additively separable, i.e., it can be represented in the form:

$$U(\mathbf{y}) = \Sigma_{g=1}^{G} U(\mathbf{y}_g) \qquad [1]$$

where $U(\mathbf{y})$ is the total utility function and $U(\mathbf{y}_g)$ is the separable utility of consuming the group of variables represented by $\mathbf{y}_g$.

At a regional level it is possible to assume that this assumption holds in multiple-use planning. The commodity bundle can be separated into groups of homogeneous commodities. This is facilitated if (i) variables are made explicit in the input/output decision space, and (ii) constraints, if any, on variables should

be explicit. The effect of these conditions is to avoid hidden pre-allocations of resources, and the construction of variables with embedded, not recognizable, and not available constraints.

Paredes and Brodie (1988a) demonstrate that when these conditions are met, the objective function for the multiple-use forest model can be additively separated into different commodity groups:

$$U(y) = U(y_m) + U(y_n) \qquad [2]$$

where y_m and y_n are, respectively, the vectors of market and nonmarket commodities. Since output levels for nonmarket goods are usually modeled as right-hand side allocations,

$$U(y_n) = \mu_n \cdot y_n \qquad [3]$$

where μ_n is the vector of shadow prices associated with an allocation of y_n.

Additionally, this modeling approach for a separable objective function satisfies the requirements for a homogeneous scaling among the groups of variables. It is known, from duality theory, that shadow prices in a general linear programming context are expressed in the same measure units as the primal objective function, i.e.,

$$\mu_n = \delta U(\cdot)/\delta y \qquad [4]$$

implies that the measure units of $\mu_n \cdot y_n$ are consistent with those of $U(y_m)$.

By expressing all valuation units in the allocation problem in terms of $U(y_m)$, the units of measure for these become the numeraire of the process. Since a close approximation to social welfare is desired, the numeraire has to be chosen accordingly. The ideas presented in the previous section suggest that a desirable property would be a resemblance of the process to a competitive market.

At the same time, it is convenient to recall here that one of the requisites forest managers and economists are recently requiring from an allocation mechanism, refers to its capability to account for cumulative effects across production units on a regional basis (Teeguarden 1987).

Both requirements are implicitly satisfied by Samuelson's "net social payoff" concept to solve for multimarket equilibrium. Even though Samuelson (1952) did not imply any social welfare significance to the net social payoff magnitudes, it has been later demonstrated by Willig (1976) that the use of consumer's surplus magnitudes provides a good approximation to the appropriate welfare measures. Willig demonstrates that both compensating and equivalent income variations are accounted for in the consumer's surplus.

Adding to the formalization of net social payoff concept, Smith (1963) demonstrated that the dual of Samuelson's spatial equilibrium problem corresponds to rent minimization of production factors.

The use of net social payoff as the numeraire in the objective function at the regional level provides an interesting and, more important, implementable measure of social welfare to drive the allocation process.

Required elements for a net social payoff function are an inverse form of demand function for each demand center in the region. These functions are econometrically derived having the general form:

$$\mathbf{P}_c = Dc(y_c) \qquad [5]$$

where $\mathbf{P}_c$ is the per unit price paid at demand center c for commodity quantities traded at that location, y_c.

The supply functions are provided either by parametric programming for those production units "controlled" by the process, as illustrated by Paredes and Brodie (1988a) in a forest-level context, or by behavior simulation or econometric analysis for those units beyond the institutional limits. Typically a supply function will have the form:

$$\mathbf{P}_p = S_p(y_p) \qquad [6]$$

where $\mathbf{P}_p$ is the per-unit marginal cost of producing the set of commodities, at level y_p at the production unit p.

Commodity flows are modeled through specific variables y_{pc} describing the bundle of commodities flowing from production center p to market location c. The associated transportation costs are generally assumed linear and described through the coefficients t_{pc}.

The objective function then takes the form:

$$\max U = \sum_c \int_0^{u_c} D_c(\tau_c)\, d\tau_c - \sum_p \int_0^{w_p} S_p(\tau_p)\, d\tau_p - \sum_{p,c} t_{pc} y_{pc} \qquad [7]$$

subject to

$$u_c \le \Sigma_p y_{pc}, \qquad \text{for all c} \qquad [8]$$

$$w_p \ge \Sigma_c y_{pc}, \qquad \text{for all p} \qquad [9]$$

where equation [8] bounds the total amount demanded at the c-th market location, and equation [9] bounds the amount of commodity supplied at the production unit p. The τ's are dummy integration variables. Equation [7] accounts to the net social payoff as the consumers' surplus less producers' surplus and transportation costs.

An objective function formulated in this way, at a regional level, addresses a topic often neglected in forest planning models, accounting transportation costs as endogenous variables. This can provide an alternative to current timber valuation methods based on a stumpage concept. While the flat stumpage approach may be appropriate for small owners, it is necessarily restrictive in a forest/regional context where the definitive impact of the main cost item (hauling) is dependent on market location. At this level market destination for timber can not be assumed away.

The same rationale applies for those forms of recreation where travel cost methods provide estimates of consumer's willingness-to-pay and therefore approximate the impact of recreation outputs into social welfare. An objective function with resolution for recreation demand centers and recreation supply units, linked through the actual transportation network, could vastly improve on current allocation methods.

Similar functional forms for the objective have been previously used in forestry planning by Greber and Wisdom (1985), although they focus on interactions in roundwood markets only, and transportation costs are not endogenous to the model. A closer form has been utilized by Fowler and Nautiyal (1986) for land allocation to agricultural, timber, mining, urban, and recreational uses. In this model, production units are defined as grid cells on a map. Both models are single-level.

The construction of an objective function which, at the regional level, approximates society's preferences on economic welfare states, provides a solid base to decompose the planning procedure to lower hierarchical levels. This achieves Kantorovich's "system of information, accounting and economic indexes and stimuli" mechanisms which makes local managers to select socially optimal actions.

Production levels and flows are technically constrained by the system of equations relating outputs and inputs for each local production unit. The following equations describe, respectively, those constraints:

$$\mathbf{w}_p - \Sigma_p \mathbf{T}_p(\mathbf{x}_p) = \mathbf{0}, \quad \text{for all p} \qquad [10]$$

$$\Sigma_p \mathbf{x}_p \leq \mathbf{b} \qquad [11]$$

where $\mathbf{T}_p(\mathbf{x}_p)$ is the production function at unit p that describes the technological relationships between inputs, $\mathbf{x}_p$, and outputs, $\mathbf{w}_p$. In a strict sense, equation [10] is redundant since the relevant information on output levels is already embedded in the objective function's term for the producer's surplus. Equation [10] is included here only for completeness when illustrating, later, the operational aspects of the model.

The symbol **b** represents the vector of initial resource endowments of the regional economy. It describes both the resource base of each production unit (land base and vegetation cover, for example) that can not be changed within the planning period, and the resources (public and private) available to the regional economy which will be consumed by the local units.

As described above, the model still does not provide an explicit treatment for production/consumption of those commodities that can not be treated with information provided by actual markets. The presence of externalities, the production impacts on public goods, and the effect of economies/diseconomies of scale are some of the "cumulative effects," as usually identified in recent forestry literature, that need to be explicitly accounted for. These are the issues, varying in emphasis from one region to another, that generally refer to the effects of policy requirements such as long-term sustained yield, wildlife habitat protection, species diversity, roadless areas conservation, and others.

These constraints are represented, generically, by the form

$$\Sigma_p \mathbf{g}_p(\mathbf{w}_p, \mathbf{x}_p) \geq \mathbf{h} \qquad [12]$$

where the function $\mathbf{g}(\bullet)$ describes the technical relationships, linear or nonlinear, between market commodities/resources and the nonmarket ones. The vector **h** describes the levels requested for nonmarket commodities. The convention that goods are desirable is followed here; for example, an element of **h** would request a minimum of the commodity "clear water," instead of constraining the maximum of "water pollution." So instead of **h** constraining, for example, water pollution requests a minimum level of clean water.

The incorporation of these outputs at a regional level is consistent with current practices in public forestry, e.g., the RPA Program of the U.S. Forest Service. Furthermore, it reduces the possibility of non-convexities that may occur associated with externalities at the forest level.

It needs however be recalled that the **h**'s are still regarded as decision variables. The regional planning authority determines their optimal values trying to emulate a Lindahl equilibrium for public goods. This will be discussed later.

The problem is therefore to maximize [7] subject to equations [8] to [12] and the usual nonnegativity constraints of the arguments **x**, and **w**.

A "one-pass" solution of the planning problem presented would be a formidable task. Each local unit would need transfer to the center the information described by the $T_p(\bullet)$ and $g_p(\bullet)$ functions. Even if the model solves for short-run allocation and it has unlimited computing facility, the problems of transferring local expertise would render the "one-pass" approach impractical. Decentralization now comes to the rescue.

For an understanding of the procedure's economics a characterization of the optimality conditions is presented.

To simplify notation let

$$R_c = \int_0^{u_c} D_c(\tau_c)\, d\tau_c \qquad [13]$$

$$R_p = \int_0^{w_p} S_p(\tau_p)\, d\tau_p \qquad [14]$$

then the Lagrangian function associated with the problem can be written:

$$\begin{aligned} L = \Sigma_c R_c - \Sigma_p R_p - \Sigma_{pc} t_{pc} y_{pc} &+ \Sigma_c \sigma_c [\Sigma_p y_{pc} - u_c] \\ &+ \Sigma_p \mu_p [w_p - \Sigma_c y_{pc}] \\ &+ \pi [\mathbf{b} - \Sigma_p \mathbf{x}_p] \\ &+ \Theta [\Sigma_p \mathbf{g}_p(w,x) - \mathbf{h}] \end{aligned} \qquad [15]$$

where σ, μ, π, and Θ are dual multipliers.

The Kuhn-Tucker conditions for optimality explain the economic rationale of the allocation process. At the demand centers, the total level of traded commodity, u_c, satisfies the following conditions:

$$u_c \geq 0,$$

$$m_c - \sigma_c \leq 0$$

$$u_c[m_c - \sigma_c] = 0, \quad \text{for all c} \qquad [16]$$

where m_c is the total consumers' willingness to pay for a consumption level u_c at demand center c, and σ_c is the imputed value of the commodity delivered at the demand center. These are usually called regional consumer equilibrium conditions and state that, for positive levels of consumption, the price paid at the market equals the imputed cost of producing the commodity and transporting it to market at c.

Transportation decisions, from production unit p to market c, satisfy:

$$y_{pc} \geq 0$$

$$-t_{pc} + \sigma_c - \mu_p \leq 0$$

$$y_{pc}[-t_{pc} + \sigma_c - \mu_p] = 0, \quad \text{for all p, c} \qquad [17]$$

These conditions regulate the flow of commodities across the region. They state that a commodity is hauled, $y_{pc} \geq 0$, if its transport cost, t_{pc}, does not exceed the price differential between its imputed values at production unit, μ_p, and at demand location, σ_c. These conditions are usually referred to as locational price equilibrium conditions.

The optimal production level at unit p, w_p is determined with the following conditions:

$$w_p \geq 0$$

$$-m_p + \mu_p + \Theta \bullet \delta g_p(\bullet)/\delta w_p \leq 0$$

$$w_p[-m_p + \mu_p + \Theta \bullet \delta g_p(\bullet)/\delta w_p] = 0, \text{ for all p} \qquad [18]$$

where m_p is the marginal cost of the commodity at the production unit p, where m_p is evaluated with the technological constraint in equation [10]. These are called the supplier's equilibrium conditions and state that a commodity is produced ($w_p > 0$) up to the level where its imputed value, m_p, equals the market value of the output, μ_p, at p, plus the value of its marginal impact in the production of non-market outputs, $\Theta \bullet \delta g_p(\bullet)/\delta w_p$.

The optimal use of resources, x_p, is specified by:

$$x_p \geq 0$$

$$\mu_p \bullet \delta T_p(x_p)/\delta x_p + \Theta \bullet \delta g_p(\bullet)/\delta x_p - \pi \leq 0$$

$$x_p[\mu_p \bullet \delta T_p(x_p)/\delta x_p + \Theta \bullet \delta g_p(\bullet)/\delta x_p - \pi] = 0,$$

$$\text{for all p} \qquad [19]$$

where π is the marginal value of production factors. These conditions state that resources are consumed up to the level where the marginal value of the resource is completely allocated among its marginal value impacts on the production of market, $\mu_p \bullet \delta T_p(x_p)/\delta x_p$, and non-market commodities, $\delta g_p(\bullet)/\delta x_p$.

The following are the market prices equilibrium conditions. They regulate commodities and resources valuations to avoid excess demand or excess supply possibilities.

$$\sigma_c \geq 0, \Sigma_p y_{pc} - u_c \geq 0$$

$$\sigma_c[\Sigma_p y_{pc} - u_c] = 0, \quad \text{for all c} \qquad [20]$$

$$\mu_p \geq 0, w_p - \Sigma_c y_{pc} \geq 0$$

$$\mu_p[w_p - \Sigma_c y_{pc}] = 0, \quad \text{for all p} \qquad [21]$$

$$\pi \geq 0, \mathbf{b} - \Sigma_p \mathbf{x}_p \geq 0$$

$$\pi[\mathbf{b} - \Sigma_p \mathbf{x}_p] = 0, \qquad [22]$$

$$\Theta \geq 0, \Sigma_p g_p(w,x) - \mathbf{h} \geq 0$$

$$\Theta[\Sigma_p g_p(w,x) - \mathbf{h}] = 0 \qquad [23]$$

The conditions in [20] and [21] determine, respectively, the consumers' and producers' behavior when facing positive prices and excess supply or demand for their commodities.

Conditions specified in [22] determine the pricing rules for resource consumed in production. Conditions in [23] guide the units' decisions on expansion of the production level of non-market outputs according to the price offered by the center.

A local manager would seek to allocate his inputs, $\mathbf{x}_p$, so as to maximize his total profits from market commodities, at prices μ_p, and from those nonmarket commodities that the center regulates, at prices Θ. Local managers solve the problem:

$$\underset{\{x_p, w_p\}}{\text{maximize}} \ \mu_p w_p + \Theta \bullet g_p(w_p, x_p) \qquad [24]$$

subject to

$$w_p - T_p(x_p) = 0 \qquad [25]$$

$$x_p \leq b_p \qquad [26]$$

$$x_p, w_p \geq 0$$

given μ_p, Θ, and b_p.

The corresponding Lagrangian to this problem is:

$$L_p = \mu_p w_p + \Theta \bullet g_p(w_p, x_p)$$

$$- \Phi_p \bullet [w_p - T_p(x_p)] + \pi_p \bullet [b_p - x_p] \qquad [27]$$

Conditions for an optimum to the local manager problem are given by:

$$w_p \geq 0, \mu_p + \Theta \bullet g_p(w_p, x_p) - \Phi_p \leq 0$$

$$w_p[\mu_p + \Theta \bullet g_p(w_p, x_p) - \Phi_p] = 0 \qquad [28]$$

$$x_p \geq 0,\ \Theta \cdot \delta g_p(\cdot)/\delta x_p + \Phi_p \cdot \delta T_p(x_p)/\delta x_p - \pi \leq 0$$

$$x_p [\Theta \cdot \delta g_p(\cdot)/\delta x_p + \Phi_p \cdot \delta T_p(x_p)/\delta x_p - \pi] = 0 \quad [29]$$

According to the definitions given in the regional problem formulation Φ_p is exactly equal to m_p. Thus the optimality conditions for a local manager, in equations [28] and [29], are equivalent to those in [18] and [19] for the global regional problem.

This clearly shows that if the center has available the correct values for μ_p, for all p, and those for Θ, then it could provide that information to the local managers and they would allocate resources and production in a socially optimal way. Alternatively, the center could set quotas on input or outputs for each firm following the ideas of Heal's quantity-guided procedure.

The regional manager's problem, after the firms have provided information on their output levels for market commodities, w_p, and their resources usage, x_p, can be stated as:

$$\max U = \Sigma_c R_c - \Sigma_c t_{pc} y_{pc} - m_p w_p - \pi \cdot [\Sigma_p x_p]$$

$$+ \Theta \cdot [\Sigma_p g_p(w_p, x_p)] \quad [30]$$

subject to

$$u_c \leq \Sigma_p y_{pc} \qquad \text{for all c} \quad [31]$$

$$w_p \geq \Sigma_c y_{pc} \qquad \text{for all p} \quad [32]$$

where equation [30] describes the center allocating consumption of the private commodities to maximize the difference between consumers surplus, $\Sigma_c R_c$, plus the social value of the nonmarket commodities, $\Theta \cdot [\Sigma_p g_p(w_p, x_p)]$, and the costs of transportation from production to consumption centers, $\Sigma_c t_{pc} y_{pc}$, plus production costs, $m_p w_p$, and the costs of resources utilized, $\pi \cdot [\Sigma_p x_p]$.

With optimality conditions given by:

$$y_{pc} \geq 0,\ -t_{pc} - \sigma_c + \mu_p \leq 0$$

$$y_{pc} [-t_{pc} - \sigma_c + \mu_p] = 0 \quad [33]$$

$$u_c \geq 0,\ m_c - \sigma_c \leq 0$$

$$u_c [m_c - \sigma_c] = 0 \quad [34]$$

which are equivalent to those given in [16] and [17] for the global regional problem.

As observed, the multiple-use forest planning problem for a regional economy is decomposable into decisions corresponding to a regional planning bureau and those associated to local unit managers. The language of the solution mechanism can incorporate either price or quota messages, or both. By letting each local manager adjust their input and output levels under his control according to the price messages received from the center, the problem is solved as in the Lange-Arrow-Hurwicz routine described in the previous section. In this case, the center would adjust its price messages proportionally to the excess demands at the commodities and resources markets. Such a routine is informationally efficient and results in Pareto-efficient allocations. However, a drawback in applying it is that the size of the problem would require to terminate the process after a finite number of iterations, possibly without ever reaching a feasible allocation.

Alternatively the problem can be solved with a price-guided routine where the center adjusts production quotas or resource consumption among local units according to their social marginal cost or to their value marginal product, respectively, as in Heal (1969). It can also be solved with a mixed price-quantity procedure as the one described by Heal (1971). These methods would guarantee a sequence of feasible solution with a monotonically increasing value of the objective function.

The selection of an iterative procedure to solve for the regional problem goes beyond the relevant scope of this analysis. The approach to planning process adopted here views it as a continuous decision making process that detects and evaluates environmental variations and, if necessary, adjusts actual operations to achieve the new equilibrium state. Therefore, each opportunity the model is solved only a few iterations become necessary to reach the new optimum. This is the property called homeostasis that characterizes optimally designed systems (Arrow and Hurwicz 1960, Beer 1972). A huge planning effort undertaken periodically every 5 or 10 years, as currently done in many forest institutions, is no longer necessary. The institution has a permanently actualized model of the planning problem.

Nevertheless, computational efficiency considerations are still important for the set-up stage of such a planning procedure, particularly when current output levels and market values are distant from the equilibrium values.

The selection of an iterative routine for the planning model just presented must also consider explicitly the particular characteristics of the resources and the nonmarket commodities represented in **b** and **h**, respectively.

Some of the resources in **b** are inherent to each local unit, such as the land base or the capacity of the internal transportation infrastructure. The central authority would benefit from the knowledge of the associated social value of these resources, as reported by π_b, to allocate the regional budget on, for example, virtual expansions of the land base through coordination with state and private lands, or construction of transportation facilities.

Other elements in **b** describe regional resources that are allocated among competing units. The annual budget is the typical example. Budget allocations are easily handled by the central authority through a quota mechanism where budgets are adjusted according to its relative social marginal productivity in each local unit. Thus each unit is required to inform its budget requirement as well as the marginal productivity of this input.

Further, some resources in **b** have the characteristics of public goods, from a local manager standpoint. The center supplies the commodity up to the level where its marginal social cost equals the sum, over all local units, of its marginal produc-

tivity effect on the market goods, $\delta T(\bullet)/\delta b$, times the marginal social value, μ_p, of the firm's output. In other words, the social value of an increment in supply of the public commodity equals the sum, over all firms, of its opportunity values if these are evaluated at shadow prices. This is clearly the case of budget allocations to fire prevention and protection systems, pest control, and research and development programs. At equilibrium for these commodities it is observed that the amount of the good demanded from each unit equals the amount supplied and, simultaneously, the marginal cost of supplying it equals the sum, over firms, of its marginal value.

For the nonmarket commodities accounted for in **h** the center does not have available an exact estimate of the society's willingness-to-pay curve, but only a crude estimate for the range of such values. Many of these commodities are typically public goods in the classical sense: protection of endangered species, ecosystem preservation, habitat diversity. In these cases, the center should price commodities such that the accumulated reactions of all firms result in an output level with opportunity cost equal to the total society's willingness-to-pay. Here the role of the center is to achieve, through a pricing mechanism, an output level that is politically acceptable to society.

At any instant, the local units allocate their resources and scheduled their outputs mix and levels such that they maximize revenues. If the prices, set by the center for the nonmarket commodities, are socially correct, then the firms will automatically allocate at the optimum for the whole economy.

Summary

In the paper we have tried to illustrate, respectively, the current approaches to forest planning and their shortcomings, the recent developments in the theory of economic analysis and management, and a design of a resource allocation model for multiple-use forest planning at the regional level.

Resolution of the conflicts raised by competing uses of the forest land require the design of resource allocation mechanisms that provide managers and interest groups with a tidy and consistent picture of the values associated to each allocation option. As a public manager once stated with respect to legislation and economics: "We need more one-armed economists who won't be able to say, 'but, on the other hand'..." (cited by Miles 1986, p. 46).

The developments in economic analysis (Hurwicz 1972) and the findings of managerial cybernetics (Beer 1972, 1979) during the last decades provide the tools required to address the complex issues of multiple-use forest management that past and current reliance on both orthodox planning concepts and generic mathematical programming tools have failed to solve.

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An Algorithm for Writing Adjacency Constraints Efficiently in Linear Programming Models

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Abstract.--Land allocation and harvest scheduling linear programming models used for small area planning often must contain large numbers of constraints that restrict activities on adjacent management units. Minimizing the number of constraints required can reduce solution times and allow larger areas to be modelled when faced with software limitations on model size. This paper presents an algorithm for efficiently writing adjacency constraints in linear programming models. The approach, which combines multiple adjacency restrictions into one constraint, typically results in less than half the constraints required by the adjacency constraint formulations commonly used in the past.

As forest management planning moves from the strategic to the operational level, the nature of linear programming (LP) models used in planning analysis changes dramatically. At the operational level of planning, models must contain much more spatial detail because activities and environmental responses must be site specific. This means that the decision variables should correspond to management activities for small contiguous units of land so that model formulations can represent the geographic location and spatial arrangement of activities.

Modelling spatial relationships is important for wildlife habitat management (Thomas et al. 1979) and for restricting sediment production for the protection of fisheries. Models used to simultaneously analyze transportation networks and land management activities must also represent the spatial relationships between the transportation network and the land management units. Also, policies that limit the size of contiguous openings require restrictions on clearcutting activities on adjacent management units.

For each of these examples, modelling the spatial relationships is done through some type of constraint. Mealey and others (1982) described the use of dispersion constraints to model the distribution of wildlife habitat. Transportation models require constraint rows to prevent nonsensical solutions which allow timber harvesting before access road construction (Kirby et al. 1980). Finally, restrictions on activities that occur on adjacent management units are modelled by using adjacency constraints. These constraints restrict the selection of decision variables for mutually exclusive management activities on adjacent management units.

Clearly, the price of spatial specificity in an LP model is increased model size for the area being modelled. Dividing a study area into many small, discrete units adds to the number of decision variables and representing spatial relationships between these variables requires additional constraint rows. Operational models often have as many constraints as variables (Jones et al. 1986). Computer resources required to solve LP models increase rapidly with model size and in particular with the number of constraints. Furthermore, in practice, problem size is usually limited by the number of constraints rather than the number of variables. Reducing the number of constraints is therefore important.

Adjacency constraints are a common constraint that have the potential to add a large number of rows to an LP model. For example, Thompson et al. (1973) found 53 common boundaries between 66 stands on the Pocomoke State Forest in Maryland. Their 12-period model required 10 constraints for each pair of adjacent stands for a total of 530 adjacency constraints. This paper will focus on a method of formulating adjacency constraints that will require writing significantly fewer constraints than conventional methods. We will describe an algorithm that will be useful in automating the process of writing adjacency constraints for planning models.

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Conventional Adjacency Constraint Formulation

Operational models for project-level decision making are often formulated as integer or mixed integer (MIP) models. Specific projects such as construction of a road or clearcutting a delineated stand become decision variables that will take on values of 1 or 0; build or do not build, cut or do not cut. When model sizes become too large to be solved by commercial MIP packages, they can be formulated as LP models with the 0-1 variables formulated as continuous variables with an upper bound of 1. Heuristic procedures such as those developed by Weintraub (1982) can then be used to achieve an integer solution. In this paper we assume that decision variables represent management activities on discrete contiguous areas of land that can only take on values of 0 or 1.

We begin our discussion of conventional formulations with a single period problem with one management alternative per unit. Each management activity is represented by the variable X_i which takes on the value of 1 if the management activity is chosen for unit i and 0 if not chosen. In conventional formulations, mutually exclusive constraints are written for each pair of units. For example, the pairwise formulation for the units in figure 1(b) would be:

$$X_1 + X_2 \leq 1$$
$$X_2 + X_3 \leq 1$$
$$X_2 + X_3 \leq 1$$

The difficulty with the conventional pairwise approach is that it requires a large number of constraints for realistic problems. For example, a simple 49-unit square checkerboard (7 rows and 7 columns) has 84 distinct adjacency conditions, and hence would require 84 pairwise constraints like those above.

Formulations for Reducing the Number of Constraints

Fewer constraints are needed if more than two adjacency conditions are represented in a single constraint. Writing such "combining" constraints can be done in a two step process.

Type 1 Inequalities

The first step is to write what we call Type 1 inequalities. The general form of these inequalities is as follows:

$$\sum_{i \varepsilon A} X_i \leq 1 \qquad [1]$$

This constraint represents the mutually exclusive conditions for a group of units such that each unit in group A is adjacent to each other unit in that group. There are three types of spatial arrangements that meet this condition. The simplest, already mentioned, is the adjacency pair illustrated in figure 1(a). Figure 1(b) illustrates the second arrangement, the adjacency triplet. The final arrangement is the quadruplet, shown in figure 1(c).

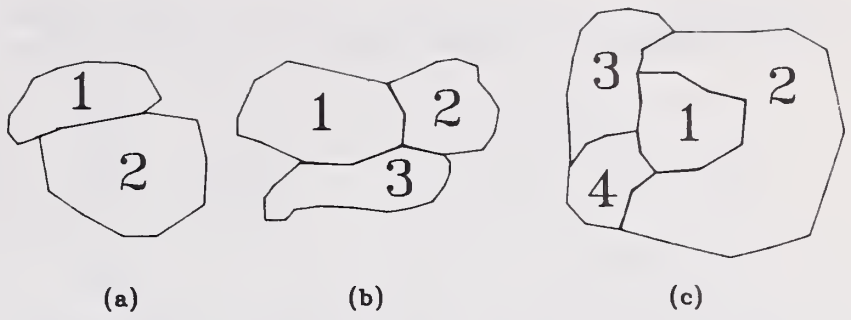


Figure 1.-- The three spatial patterns that can be represented with Type 1 adjacency constraints: the pair (a), the triplet (b) and the quadruplet (c).

We will refer to these spatial arrangements as Type 1 patterns. The constraints for these three cases for one time period and one management alternative take the form of equation [1] as follows:

Pair: $X_1 + X_2 \leq 1$

Triplet: $X_1 + X_2 + X_3 \leq 1$

Quadruplet: $X_1 + X_2 + X_3 + X_4 \leq 1$

To represent the adjacency conditions in these three arrangements with pairwise constraints would require 10 constraints (1 for the pair, 3 for the triplet and 6 for the quadruplet).

Type 2 Inequalities

Often there are opportunities to further reduce the number of constraints by means of a second type of combining formulation, called Type 2 inequalities. A single Type 2 inequality can be substituted for a set of Type 1 inequalities, R, under the following conditions:

If:

$$\sum_{i \varepsilon E} X_i + X_i \leq 1 \qquad [2]$$
$$i \varepsilon P$$

and:

$$\sum_{i \varepsilon E} X_i + \sum_{i \varepsilon G} X_i \leq 1 \qquad [3]$$

and:

$E \cap P \cap G = \emptyset$ (E intersect P intersect G equals null set)

Then: the inequalities in Set R can be combined into a single Type 2 inequality of the following form:

$$(2r-1)\sum_{i \varepsilon E} X_i + \sum_{i \varepsilon P} X_i + (r) \sum_{i \varepsilon G} X_i \leq (2r-1) \qquad [4]$$

Where:

Set R = the Type 1 inequalities meeting the conditions set forth by equations [2] and [3]

r = the number of Type 1 inequalities in Set R

Set E = projects that are present in each of the inequalities in set R

Set P = projects that are present in only one inequality in set R

Set G = projects that are members of a group present in only one inequality in set R

The adjacency relationships between the five units in figure 2(b) can be represented by three Type 1 constraints as follows:

$$X_1 + X_2 + X_3 \leq 1 \qquad [5]$$

$$X_3 + X_4 \leq 1 \qquad [6]$$

$$X_3 + X_5 \leq 1 \qquad [7]$$

These three inequalities meet all the conditions to allow them to be combined into one Type 2 inequality. First, there is at least one variable, X_3, that is present in all three Type 1 constraints. This variable makes up set E. The remaining variables in inequality [5], X_1 and X_2, satisfy the conditions of set G and equation [3]. The remaining variables of inequalities [6] and [7] individually meet the conditions of set P and equation [2]. Therefore, inequalities [5], [6] and [7] form a set R that can be combined into one Type 2 inequality according to the general form of equation [4]:

$$5(X_3) + X_4 + X_5 + 3(X_1) + 3(X_2) \leq 5 \qquad [8]$$

The general form of equation [4] represents the six basic combinations of the three Type 1 patterns shown in figure 1. These combinations, referred to as Type 2 patterns are:

1. Triplet combined with m Pairs, shown in figure 2
2. Quadruplet combined with m Pairs, shown in figure 3
3. Quadruplet combined with m Triplets, shown in figure 4
4. m Pairs combined, shown in figure 5
5. m Triplets combined, shown in figure 6
6. m Quadruplets combined, shown in figure 7

An Algorithm for Combining Adjacency Constraint Rows

This section presents an algorithm for writing a reduced set of adjacency constraints that represent all of the adjacency relationships between a group of units. The algorithm consists of two steps: in step 1 the Type 1 inequalities are identified and in step 2 they are combined into Type 2 inequalities.

Identifying Type 1 Patterns

The first step is to identify a set of Type 1 inequalities that represents the adjacency relationships for all the units in an area. This is accomplished by creating an adjacency matrix with a row and column for each unit. If two units are adjacent, the intersections of their respective rows and columns are marked, otherwise the cells remain blank. Since the completed matrix is symmetrical along the principal diagonal, only half of the matrix is used.

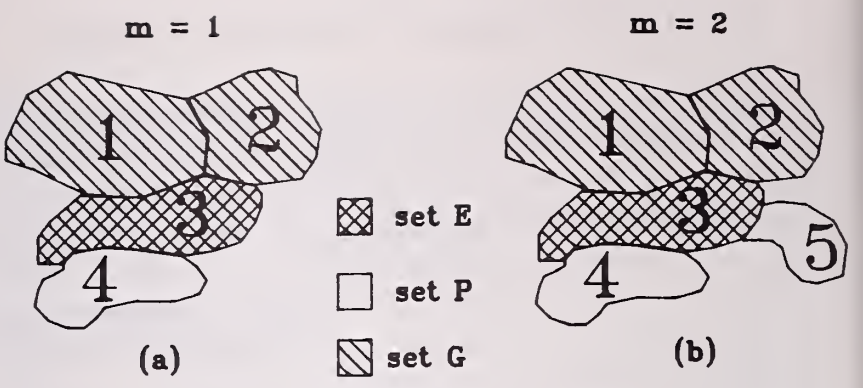


Figure 2.-- Type 2 patterns comprised of a triplet and m pairs. Triplet 1-2-3 and pair 3-4 make up (a). Triplet 1-2-3 and pairs 3-4 and 3-5 make up (b).

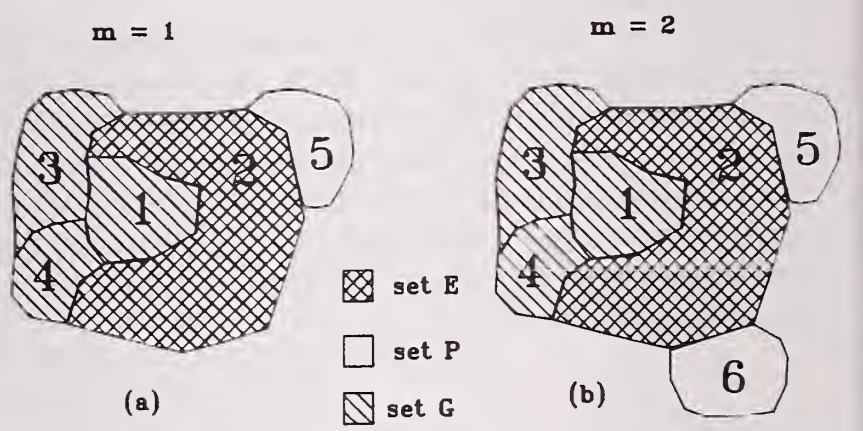


Figure 3.-- Type 2 patterns comprised of a quadruplet and m pairs. Quadruplet 1-2-3-4 and pair 5-2 are shown in (a). Quadruplet 1-2-3-4 and pairs 2-5 and 2-6 are shown in (b).

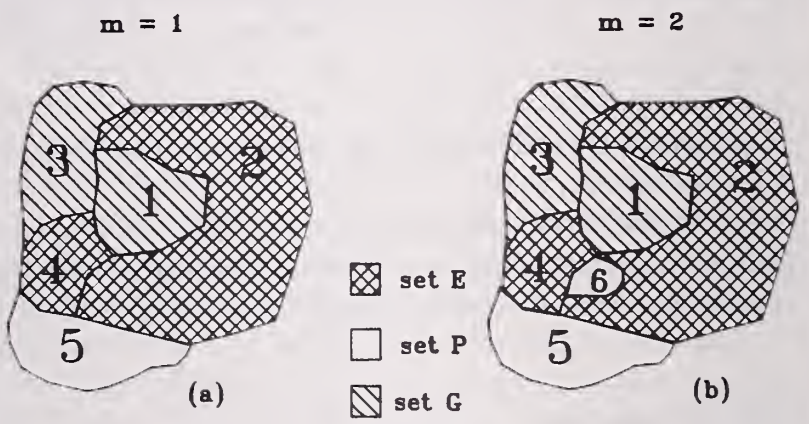


Figure 4.-- Type 2 patterns comprised of a quadruplet and m triplets. Quadruplet 1-2-3-4 is shown with triplet 2-4-5 in (a) and with triplets 2-4-5 and 2-4-6 in (b).

Consider an example. Figure 8 shows a group of units and the associated adjacency matrix. Figure 9 illustrates the steps for identifying triplets and quadruplets in this matrix. The search begins with the first marked intersection (D,A), which means units D and A are adjacent. If both units D and A are adjacent to a third unit, they are part of a triplet and there will exist some row that contains marked intersections in columns A and D. Figure 9(a) shows that row C meets this condition. Therefore,

units D, A and C form a triplet. If units D, A and C are members of a quadruplet then another row will exist that contains marked intersections in columns A, D and C. Figure 9(b) shows that row B meets this condition. Therefore, units D, A, C and B form a quadruplet.

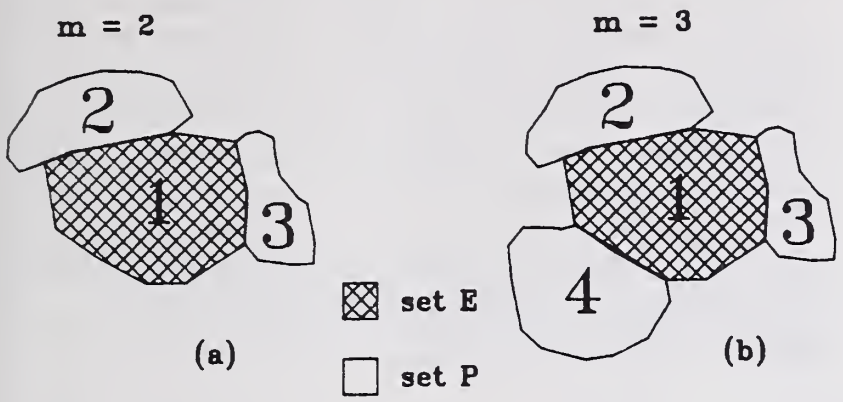


Figure 5.--Type 2 patterns comprised of m pairs. Pairs 1-2 and 2-3 are shown in (a). Pairs 1-2, 1-3 and 1-4 are shown in (b).

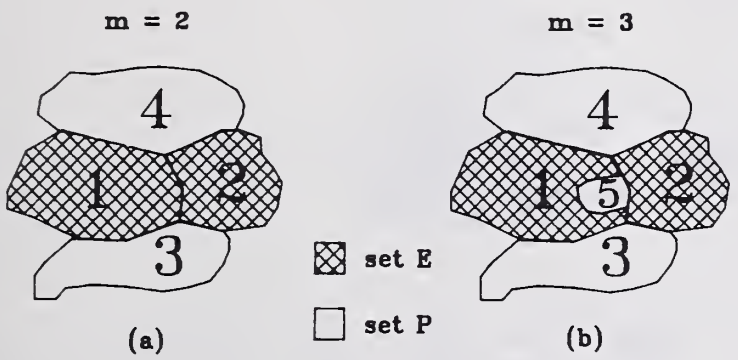


Figure 6.-- Type 2 patterns comprised of m triplets. Triplets 1-2-3 and 1-2-4 make up (a) and triplets 1-2-3, 1-2-4 and 1-2-5 make up (b).

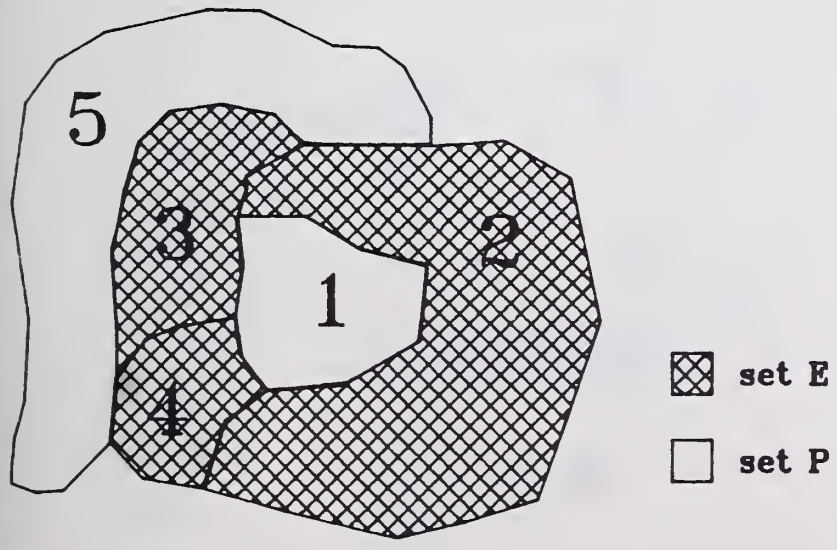


Figure 7.--A Type 2 pattern comprised of two quadruplets. Quadruplets 1-2-3-4 and 2-3-4-5 are shown.

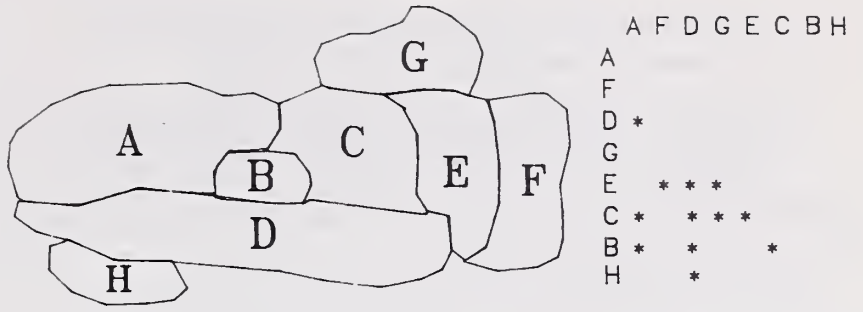


Figure 8.--A group of adjacent units and the lower half of their adjacency matrix.

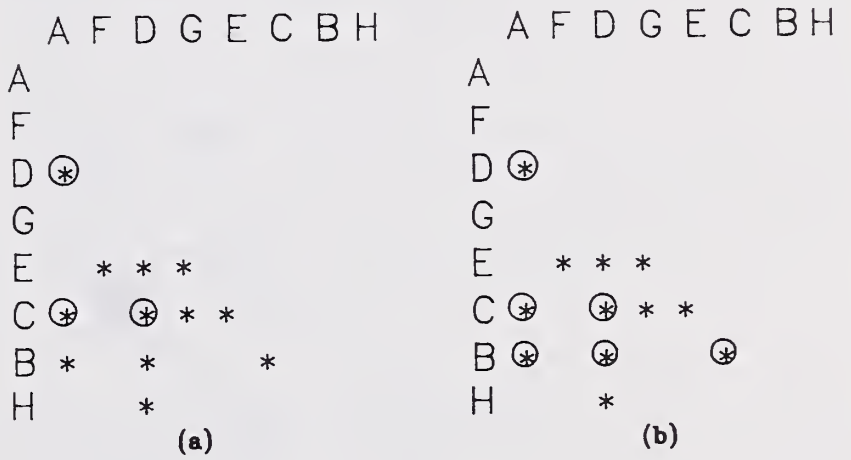


Figure 9.-- The adjacency matrix for the areas shown in figure 8. The identification of triplet A-C-D is shown in (a). The identification of quadruplet A-C-D-B is shown in (b).

The entire adjacency matrix is searched according to the following procedures and rules:

1. Each marked intersection is checked starting in the upper left part of the matrix and moving down each column.
2. At each marked intersection, the section of the matrix below and to the right of it is examined for the conditions that identify a quadruplet or triplet as described above. Quadruplets are identified before triplets.
3. If a quadruplet or triplet is found the marked intersections that make up the pattern are circled as in figure 9.
4. When a quadruplet or triplet is identified it is recorded as a type 1 pattern if the following conditions are met:
   a. For a quadruplet, at least two of the marked intersections in the quadruplet must not be circled.

b. For a triplet, at least one of the marked intersections in the triplet must not be circled.

5. Any marked intersections that cannot be included in a quadruplet or triplet are recorded as Type 1 pairs.

The left half of figure 10 illustrates the results of applying this procedure to the units in figure 8.

Combining Type 1 Constraints into Type 2 Constraints

The next objective is to combine the Type 1 constraints into the smallest number of Type 2 constraints that satisfy the adjacency conditions for each unit. To represent all of the adjacency relationships, each of the Type 1 constraints created in the first step must be represented in the final set of constraints either by itself or imbedded in a Type 2 constraint. To do this, all possible Type 2 constraints are identified, then a subset of these is chosen such that all of the Type 1 constraints that were combined into Type 2 constraints are present in the subset.

Table 1 summarizes the process of identifying all possible Type 2 constraints. First, each Type 1 is listed and labeled as in the first two columns of table 1. For each Type 1, all possible combinations with other Type 1's below it that meet the conditions of a Type 2 constraint are recorded as in the third column of table 1 (combinations are listed as a set of Type 1 labels). Finally, the total number of Type 2 constraints of which each Type 1 is a member (referred to as the Type 2 frequency) is recorded as in the fourth column of table 1. The right half of figure 10 illustrates the results of the process just described.

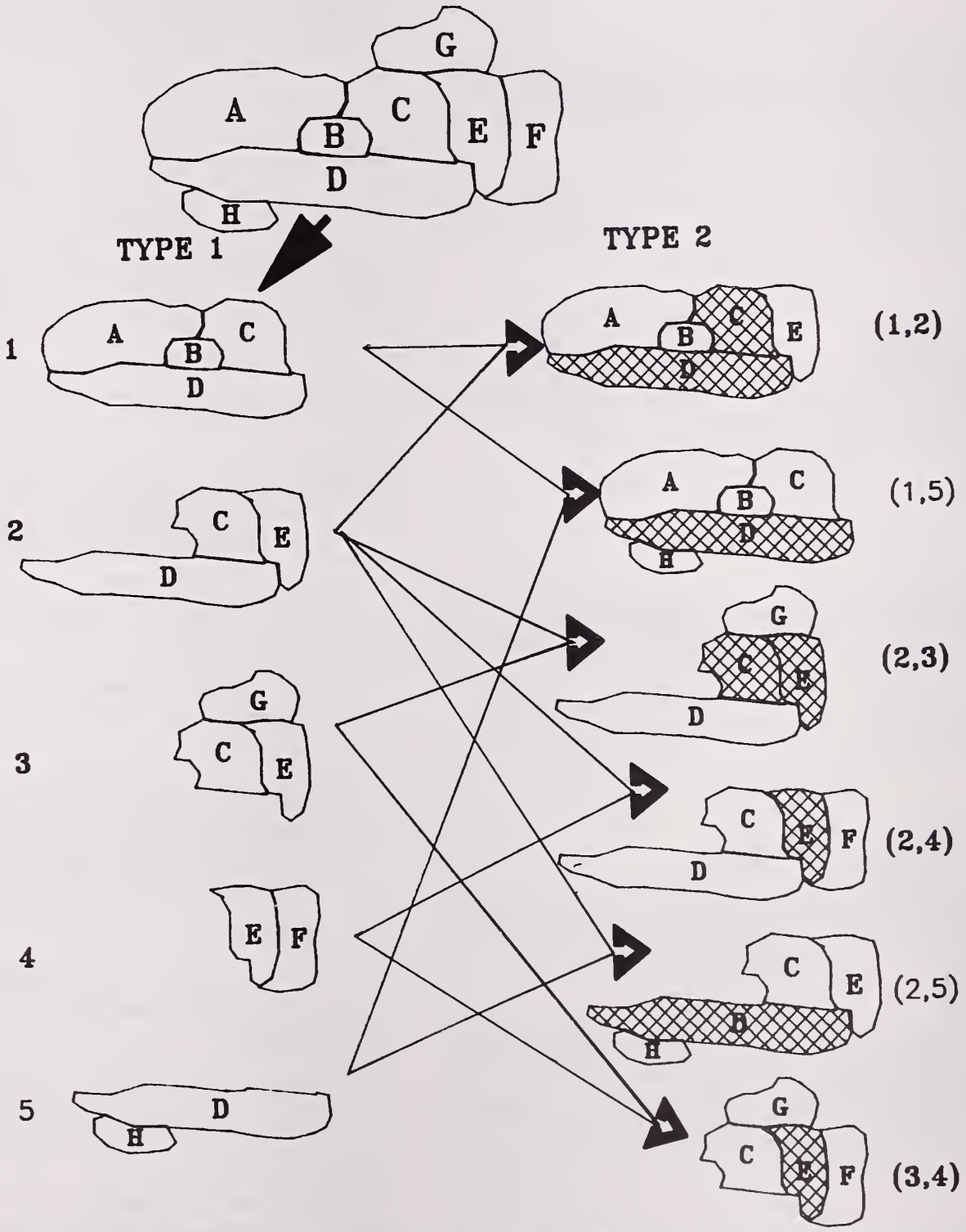


Figure 10.--A group of units is first broken down into Type 1 patterns. These patterns are then combined to form Type 2 patterns.

Table 1.--Type 1 and possible type 2 patterns for the units shown in figure 8.

Type 1 label	members	Possible Type 2 patterns	Type 2 frequency
1	A-B-C-D	(1,2),(1,5)	2
2	C-D-E	(1,2),(2,3),(2,4),(2,5)	4
3	C-E-G	(2,3),(3,4)	2
4	E-F	(2,4),(3,4)	2
5	D-H	(1,5),(2,5)	2

Table 2.-- Steps taken to choose a final set of adjacency constraints for the units shown in figure 8. The Type 1 and Type 2 patterns are defined in table 1.

Type 1 pattern	Type 2s to choose from	Choice	Decision rule
1	(1,2),(1,5)	(1,5)	Rule 4b; lower combined Type 2 frequency
3	(2,3),(3,4)	(3,4)	Rule 4b; lower combined Type 2 frequency
4	(2,4),(3,4)	--	Rule 1; skip because already included in (3,4)
5	(1,5),(2,5)	--	Rule 1; skip because already included in (1,5)
2	(1,2),(2,3), (2,4), (2,5)	(2)	Rule 4c; '2' is the only remaining Type 1 member

Table 2 summarizes the process of choosing which Type 2 constraints will be present in the final constraint set. First, the Type 1 constraints are listed by ascending order of their Type 2 frequency as in the first column of table 2. For each Type 1, the Type 2s of which it is a member is listed beside it (the second column of table 2) and one is chosen for the final constraint set according to the following rules:

1. If the Type 1 constraint has been included in a Type 2 constraint chosen previously then go on to the next Type 1.

2. If the Type 1 constraint is present in no Type 2 constraints then it is included "as is" in the final constraint set.

3. If the Type 1 constraint is present in only one Type 2 constraint and there is more than one remaining Type 1 in that set then that Type 2 constraint is chosen for the final constraint set. If there is only one remaining Type 1 then that Type 1 is included "as is" in the final constraint set.

4. If the Type 1 constraint is present in more than one Type 2 constraint, the choice follows this hierarchy:

   a. The Type 2 constraint containing the most Type 1 constraints not already included in a chosen Type 2 is chosen first.

   b. If two or more Type 2 constraints contain equal numbers of remaining Type 1 constraints, rank them according to the combined Type 2 frequency of their individual Type 1 members. The Type 2 with the lowest combined frequency is chosen first.

   c. If all the Type 2s contain only one remaining Type 1 then that Type 1 is included "as is" in the final constraint set.

Please refer to table 2 as we illustrate this procedure for the units in figure 10. Pattern '1' is included in two Type 2s ('(1,2)' and' (1,5)'). The Type 2 frequency for '(1,2)' is 6 while the Type 2 frequency for '(1,5)' is 4. Therefore, '(1,5)' is chosen. Considering pattern '3' next, there are two Type 2 patterns to choose from ('(2,3)' and '(3,4)'). Pattern '(3,4)' is chosen because its combined Type 2 frequency is lower than that of '(2,3)' (4 vs. 6). Type 1s '4' and '5' are skipped because they are included in Type 2s already chosen. Finally, considering pattern '2' we see that all the Type 1s with which it is paired have already been included in previous choices. Therefore, '2' is included "as is" in the final constraint set. For this example, the final constraint set would be reduced to only three equations as follows:

Combine	(1):	A +		B+		C +		D					≤1
and	(5):							D+				H	≤1
to get		2(A)+		2(B)+		2(C)+		3(D)+				H	≤3
Combine	(3):					C +			E +		G		≤1
and	(4):								E +	F			≤1
to get						2(C)+			3(E)+	F	+2(G)		≤3
Use (2) as is:						C +		D+	E				≤1

To represent the adjacency relationships for these units with pairwise constraints would require 11 constraints.

Representing Multiple Projects and Periods

Thus far, we have considered units with only one potential project occurring in one time period. However, many operational models have alternative management and timing choices. In some cases, more than one period must elapse between activities on adjacent units. For these cases, Type 1 and Type 2 formulations are extended.

For models with multiple periods and management alternatives each management activity is represented by the variable X_{ilt} which takes on the value of 1 if alternative activity l is chosen for unit i during time period t and takes on the value of 0 if not chosen.

Adjacency constraints for models with these variables are written by reducing the variables to a simple form as in equation [1] (one time period and one project), applying the combining algorithm and finally extending the Type 1 and Type 2 inequalities of the final constraint set to include multiple periods and projects. The general form of the extended inequalities is as follows:

Type 1: $Y_a \leq 1$ [9]

Type 2: $(2r-1)(Y_c) + (Y_p) + (r)(Y_g) \leq (2r-1)$ [10]

Where

$$Y_a = \sum_{i \varepsilon A} \sum_{l=1}^{L} \sum_{t=q}^{q+n-1} X_{ilt}$$

$$Y_c = \sum_{i \varepsilon E} \sum_{l=1}^{L} \sum_{t=q}^{q+n-1} X_{ilt}$$

$$Y_p = \sum_{i \varepsilon P} \sum_{l=1}^{L} \sum_{t=q}^{q+n-1} X_{ilt}$$

$$Y_g = \sum_{i \varepsilon G} \sum_{l=1}^{L} \sum_{t=q}^{q+n-1} X_{ilt}$$

L = the number of mutually exclusive management choices for unit i

n = the number of periods that must pass between activities on adjacent units (n = 1 means activities cannot occur on adjacent units in the same period, n = 2 means they cannot occur within two consecutive periods and so on)

q = the beginning time period for the constraint

and all other notation is as previously defined.

To illustrate we will consider the units in figure 8. We have shown how the adjacency relationships for these units can be represented with two Type 2 and one Type 1 inequalities. For a case with two management alternatives and two time periods with n = 1, the inequalities for the Type 1 pattern comprised of units C, D and E would be:

$$t=1:\ X_{C11} + X_{C21} + X_{D11} + X_{D21} + X_{E11} + X_{E21} \leq 1$$

$$t=2:\ X_{C12} + X_{C22} + X_{D12} + X_{D22} + X_{E12} + X_{E22} \leq 1$$

The Type 2 pattern comprised of units G, C, E and F can be extended as follows:

$$Y_e = t=1:\ X_{E11} + X_{E21}$$
$$\quad\ t=2:\ X_{E12} + X_{E22}$$
$$Y_p = t=1:\ X_{F11} + X_{F21}$$
$$\quad\ t=2:\ X_{F12} + X_{F22}$$
$$Y_g = t=1:\ X_{G11} + X_{G21} + X_{C11} + X_{C21}$$
$$\quad\ t=2:\ X_{G12} + X_{G22} + X_{C12} + X_{C22}$$

Therefore by substitution into equation [10] we get:

$$t=1:\ 3(X_{E11}) + 3(X_{E21}) + (X_{F11}) + (X_{F21}) + 2(X_{G11}) + 2(X_{G21}) + 2(X_{C11}) + 2(X_{C21}) \leq 3$$

$$t=2:\ 3(X_{E12}) + 3(X_{E22}) + (X_{F12}) + (X_{F22}) + 2(X_{G12}) + 2(X_{G22}) + 2(X_{C12}) + 2(X_{C22}) \leq 3$$

Test Cases

The algorithm was tested with data for sub-units of planning areas on three National Forests (NF): the Twin Rocks area of the Lolo NF, the Bonetti compartment of the Eldorado NF and the Big Springs area of the Kaibab NF. Two methods were used to determine the final constraint set. In addition to the algorithm described above, an integer programming model was used to choose the final set of Type 2 inequalities from the "all possible" set of Type 2 inequalities.

In this model, the number of Type 2 constraints was minimized, subject to the condition that each of the Type 1 patterns is imbedded in the final set of Type 2 constraints. This integer programming method provides a baseline for measuring the goodness of the last step of the combining algorithm described above. The results of the comparison, presented in table 3, show little difference between the algorithm and the method using integer programming.

These test cases, together with many smaller hypothetical problems tested by the authors, indicate some general patterns in the required number of Type 1 and Type 2 constraints. Test results show that if the majority of the units in an area have between 3 and 5 adjacent units then the number of adjacency conditions is about twice the number of units.

For this type of area, the number of Type 1 patterns is generally half the number of adjacency conditions. These Type 1 patterns can usually be combined into Type 2 patterns to reduce the number by half again. Estimates of the total number of constraints required can then be made based on the number of time periods in the model, T, and the length of time that must pass between mutually exclusive management activities, n. If S is the total number of Type 1 and Type 2 patterns after combining, the total number of adjacency constraints required to represent the adjacency relationships is S x (T-n+1).

Table 3.--Adjacency relationships on three national forest test areas and the results of applying the adjacency constraint reduction algorithm.

	Twin Rocks	Bonetti	Big Springs
Management units	28	41	56
Adjacency conditions (maximum type 1 pairs)	53	88	108
Type 1 patterns after Step I	30	46	60
Type 2 patterns after Step II			
integer programming method	15	22	28
algorithm	15	23	30

Conclusions

This paper has presented some alternative formulations for spatial relationships used in linear programming models for analyzing forest management alternatives. The underlying objective of the formulations is to reduce the number of constraints necessary to formulate adjacency constraints. In some instances, the savings are large. For the three areas studied up to a four fold decrease in the number of constraints was achieved over what would be required if the constraints were written pairwise.

Mathematical programming models constructed for operational forest management planning, by their nature, contain a large number of constraints relative to strategic planning models. The reduction in the number of constraints required to formulate the adjacency relationships, as discussed in this paper, is expected to have some combination of the following payoffs.

First, the cost of solving a mathematical programming problem is relatively sensitive to the number of constraints in the model. Reducing the number of constraints can be expected to reduce the cost of solving these models. Second, the number of constraints is usually the most limiting dimension on size for models of this type. Space saved by the formulations discussed in this paper can be used for additional constraints that model other spatial aspects of a problem or for additional decision variables that require additional constraints.

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Accounting for Stochastic Variation in Linear Programming Technical Coefficients

James B. Pickens and John G. Hof[1]

Abstract.--Two recent studies by the authors (and others) dealing with stochastic production coefficients in land allocation linear programs are discussed. One major conclusion, which was reached independently in both studies, is that selection of truly feasible solutions are unlikely if technical coefficients are random.

During recent years, operations research methods have been used increasingly in forest resource planning. Although other operations research techniques are used, linear programming (LP) is by far the most commonly employed method. LP applications are typically based on an assumption that the required data are known with certainty. This assumption is usually not tenable in forest resource planning problems. Nearly all of the required data are subject to sampling or measurement errors and/or measure intrinsically random phenomena.

A traditional approach for evaluating the effects of this unsatisfied assumption is to parametrically vary some of the data values. This approach is most often used for evaluating coefficients in the objective function or right-hand-side (RHS) values. Parametric analysis is useful to assess the impact of stochastic data if only a small portion of the extremely large number of data entries in a large LP are to be perturbed. However, this approach is not reasonable in a situation where production or cost information is suspect in large scale problems, i.e., in the case of a stochastic constraint matrix (A matrix). If parametric analysis were attempted on the constraint matrix for a realistic land allocation problem, then an impossibly large number of options would need to be evaluated and a meaningful method of solution comparison would have to be developed. This does not seem to be a viable approach for large-scale problems.

A related method of testing sensitivity to stochastic entries is chance constrained LP (Charnes and Cooper 1963). This method was applied to forage production by Hunter et al. (1976). Since this method deals with only systematic variation of production requirements or input levels (i.e., RHS's), it is not appropriate for dealing with stochastic production coefficients.

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The purpose of this paper is to assimilate two recent works by the authors and others (Hof et al. in press, Pickens and Dress in press) concerning the impact of stochastic production coefficients in renewable resource linear programs. The research conducted by Hof et al. is directed toward the problem of optimization and the "fallacy of averages" (Wagner 1975) when the means of the stochastic production coefficients are known, while the research by Pickens and Dress describes solution characteristics that are to be expected when production estimates contain a random component in land allocation problems. A brief description of the approaches and results of the two studies follows.

The Hof, Robinson, and Betters Study

Theory

As stated above, this research focuses on the case where production (yield) coefficients are random, but with known means. Two related textbook (Wagner 1975) theorems are utilized:

(I) FALLACY OF AVERAGES. Given an arbitrary nonlinear function $f(x_1,..., x_n)$ of random variables $x_1,..., x_n$, it is usually *erroneous* to assume

$$E[f(x_1,..., x_n)] = f(E[x_1],..., E[x_n]).$$

A linear case of particular interest is if we wish to:

$$\text{maximize } \sum_{j=1}^{n} c_j x_j$$

subject to

$$\sum_{j=1}^{n} a_{ij}x_j \begin{matrix} > \\ = \\ < \end{matrix} b_i \quad \text{for } i = 1, 2,..., m$$

$$x_j \geq 0 \quad \text{for } j = 1, 2,..., n, \text{ then}$$

(II) LINEAR CERTAINTY-EQUIVALENCE THEOREM. Assume that all the a_{ij} and b_i are known exactly, but the c_j are random variables independent of all x_j. If the levels of x_j, for j = 1,..., n, must be set prior to knowing the exact values of c_j, then a solution to:

$$\text{maximize } E\left[\sum_{j=1}^{n} c_j x_j\right]$$

subject to the constraints, is given by levels for x_j that

$$\text{maximize } \sum_{j=1}^{n} E[c_j]x_j$$

subject to the constraints.

Renewable resource linear programs are typically constrained by land area and/or resource yield constraints. This paper distinguishes two cases: one where only land area constraints are included, and a second where both land area and yield constraints are included. In the former case, it is shown that production coefficients actually enter the problem as objective function coefficients. Thus, Theorem II indicates that the expected value of the objective function (call it π) can be maximized simply by using the expected values of the production coefficients and solving with ordinary LP. It is also shown that, in this former case, the maximum expected value of π is not equivalent to the expected value of maximum π. This distinction is also important in the latter case. And, it is noted that the expected value of maximum π is typically not associated with any one particular solution vector.

In the latter case, the expected value of the objective function is still equivalent to the objective function based on expected values of coefficients--there is no fallacy of averages in the objective function values. In this case, however, randomness in the A-matrix coefficients persists, so the question of feasibility is difficult to address. Any given solution would only have some (generally unknown) probability of being feasible. Attempting to assure feasibility with 100% certainty would generally lead to extreme (plus or minus infinity) solutions, depending on the distributions of the A_{ij}.[2] Thus, maximum $E(\pi)$ is generally *indeterminate* with yield constraints, in the sense that it is not calculable. Conversely, postulating that the E(maximum π) is desired makes the problem determinate, in the sense that E(maximum π) is calculable but feasibility is uncertain in both circumstances.

[2]Another approach would be a type of "chance-constrained" formulation. Unfortunately, in contrast to the chance-constrained formulations with random right-hand-sides, this formulation has no apparent solution procedure, even with a simulation approach. Also, this formulation may or may not be consistent with a decision maker's desired solution.

The paper concludes that a risk-neutral formulation of the area and yield constrained problem is not clearly available. The only approach to the area and yield constrained problem that is solvable and has a determinate solution is to find E(maximum π). Common practice has been to treat the A_{ij} as deterministic. If this assumption is untenable, but we assume that the production coefficients utilized are expected values, then common practice is equivalent to this approach, except for the fallacy of averages defined in theorem (I). In order to investigate the implications of current common practice, a null hypothesis was adopted that these two approaches are empirically identical. This null hypothesis was tested in a test case with both area and yield constraints.

Case Study

The case study is designed so as to emulate the actual process typically used to develop a timber harvest scheduling LP model, with the random variation in yields based on empirical observations, rather than an assumed distribution. Field data from a single 10-point timber inventory plot sample (USDA Forest Service 1976) was obtained for a stand of mixed conifers in western Montana. A bootstrap technique (Diaconis and Efron 1983) was used to generate a "population" and 20 random samples. The procedure was to draw 62 trees from the original 62 observations, one at a time, with replacement. This was repeated 20 times, yielding the bootstrap equivalent of 20 samples (each with 62 observations) of the population. The bootstrap approach implicitly assumes that the original sample captures the variability of the population. In typical timber inventories, the population characteristics are not known.

Twenty different (small) linear programs were built, one for each of the twenty different sets of yield predictions (but identical otherwise). The problem was to schedule harvesting options over eight 10-year time periods and two land areas so as to maximize discounted net revenue, subject to management constraints. The mean of the 20 maximized objective functions was interpreted as an estimate of the expected value of the maximum objective function (π). Another linear program was also solved utilizing the mean yield coefficients. This solution represented current common practice.

The estimate of the expected value of the maximum objective function value was less than one percent less than the optimal objective function value using mean yield coefficients. The fallacy of averages is indicated to be quite small in this simple case example. The stochastic variation in the 20 different bootstrap samples resulted in substantially different acreage allocations; however, the average of the 20 different allocations (an estimate of the expected value of the optimal allocation), was quite similar to the allocation based on mean coefficients. The question of feasibility remains. The solution (allocation) based on the mean yield coefficients was imposed on the 20 different bootstrap sample coefficient sets, and infeasibilities resulted in *all 20* models. This raises questions as to the

appropriateness of the expected value of the maximum objective function as a postulated decision criterion.

The study drew the following conclusions: If only area constraints are included, current practice is equivalent to maximizing the expected value of the objective function (π), because the yield coefficients actually enter the problem as objective function coefficients. This is not equivalent to the expected value of maximum π. If both area and yield constraints are included, then constraint coefficients are unavoidably random and the maximum expected value of π is indeterminate because of uncertain feasibility. If an "acceptable probability of feasibility" can be specified, the maximum expected value of π would be, in principle, determinate, but no solution procedure for this formulation appears to be available at this time. The expected value of maximum π is determinate with both area and yield constraints, and can be estimated with simulation techniques as in the case study. However, no single solution is associated with this value, and feasibility is still uncertain (with unknown probability). The only distinction between this approach and current practice is the fallacy of averages caused by the nonlinearity between the expected value of maximum π and the technical coefficients. The case study indicates that this fallacy of averages may not be large. If this empirical finding is representative, then current practice may generate approximations to the expected value of maximum objective function values and the expected value of the optimal solution (acreage allocation). However, the case study also implies that current practice may lead to solutions that have low probabilities of being feasible.

The Pickens and Dress Study

As stated above, the central question of this research was: What solution characteristics are to be expected when production estimates with a random component are used in land allocation problems?

To address this problem a test land allocation model was developed and a simulation approach was employed. The model used data originally developed for the 1980 Assessment required by the Renewable Resource Planning Act. The data generation instructions are documented in the Book of Procedures (USDA Forest Service 1977). The test model does not include dynamic allocation over time, but is quite large with 292 analysis areas and about 10 prescriptions per analysis area. The large size was required to allow development of statistical arguments about the distribution of the solution parameters discussed below. The large model size is one major point of divergence between the methods used in the two studies discussed in this paper.

Thirty simulations for each of several model structures were run. The model structures can be classified into two distinct groups: unconstrained models (except for land area constraints) which employ several different error structures (probability density function and degree of variability) for perturbing production estimates; and constrained models using only normally distributed random deviates with a coefficient of variation of 0.1. All simulations maximized present value as the objective function.

For the unconstrained models, simulations using three error distributions, the normal, Cauchy, and double exponential, were conducted. However, only the simulations with normal random deviates will be discussed here. Separate simulations were run for three different coefficients of variation, 0.1, 0.3, and 0.5.

Two random variables were observed for each simulation. The first random variable observed was the value of the objective function when the perturbed production estimates were employed and the linear program was solved. This is referred to as the perturbed objective function value. The other random variable observed is the value of the objective function when the original (and assumed correct) production estimates are used to evaluate the objective function using the optimal decision variable activities from the perturbed problem. This random variable is called the true objective function value. The relationship of these random variables is important. The perturbed objective function would be all that is observed in an actual application with stochastic production coefficients. The true objective function represents the expected return when the optimal solution of the perturbed problem is actually implemented.

In order to evaluate the simulation results, the original problem, with no random errors applied, was solved. This solution is referred to as the base solution, and represents the result if perfect information were available.

Two additional random variables can be calculated using the base solution objective function value and the two previously defined random variables. The bias is calculated as the perturbed objective function value minus the true objective function value, and represents the amount that the perturbed objective function would deviate from the true response of the system. The loss is calculated as the base solution objective function value minus the true objective function value, and represents the potential gain to be expected if perfect information were available for planning.

The Effects of Stochastic Production Coefficients on Unconstrained Model Solutions

The following conclusions were drawn concerning the impact of stochastic production coefficients in the unconstrained case:

1. The perturbed objective function produces biased estimates of the actual response of the system, the true objective function value. The bias is positive (optimistic).

2. The distribution of the resulting true objective function, the perturbed objective function, and the bias were tested for divergence from normality.

Both the bias and the perturbed objective function appeared to be normally distributed, while the true objective function was significantly different from normal. These distributional results would be expected to vary significantly if small land allocation problems were used for similar testing because the rational for normally distributed results requires large sample sizes.

3. The perturbed objective function was distributed with a mean higher than the base solution value.
4. The true objective function will always be less than or equal to the base solution. This absolute upper limit is the reason that the true objective function was not normally distributed.
5. As would be expected, loss and bias both increased with coefficient of variation.

The Effects of Stochastic Production Coefficients on Constrained Models

Two different types of constraints were considered to evaluate the impact of stochastic production coefficients on constrained models. These two constraint types are:

1. Constraints which cannot be rendered infeasible by the stochastic production coefficients. An example of this type of constraint is a budget constraint when management costs do not vary with production level.
2. Constraints which involve the stochastic production coefficients, and therefore can be rendered infeasible in the original problem when the optimal solution of the perturbed problem is imposed.

The simulations for constrained models were restricted to normal errors with a 0.1 coefficient of variation. Only one constraint was applied to evaluate the impact of each type of constraint.

The Case Where Continued Feasibility Is Assured

To simulate the case where feasibility could not be affected, a budget constraint limiting expenditures to 80 percent of the base budget was applied. The simulation results were similar to those observed in the unconstrained simulations discussed above. Conclusions one through four listed above still held in this case.

One additional type of information is available for comparison with constrained problems--the dual activity for the global constraint. Interestingly, the dual activities observed in the simulations were significantly different than the dual activity observed for the base cost constrained solution, which used the original data without random perturbations to the production coefficients. This indicates that, when stochastic production coefficients are used, the dual activities observed are biased estimates of the values that would be observed if the correct production information were used. In this case the constraint appears more costly than it would really be. This can be explained by recalling that the optimization selectively chooses options with large positive errors in estimated production. Since the options being selected are optimistic estimates, the budget constraint implies a greater reduction in production than would really occur.

The Case Where Feasibility Is No Longer Assured When Global Constraints Are Applied

For the case where feasibility could be affected, a timber harvest constraint set at 1.2 times the base timber harvest was imposed. Conclusions one and three from above are still true. Conclusion two and four must be modified somewhat. From conclusion two, the bias and perturbed objective functions still appear to be normally distributed. However, the true objective function, which previously did not appear to be normally distributed, appears to be normally distributed in this simulation. This can be explained by the fact that conclusion four, that the true objective function value is bounded above by the base objective function value, is no longer true. Because feasibility is not assured, the optimal solution to the perturbed problem need not be feasible when imposed on the original, and assumed correct, problem.

The dual activity of the timber-constrained simulations were, as in the cost-constrained case, biased estimates of the base dual activity. The base dual activity was -0.476798, while the mean of the simulations was -0.327695. These values were significantly different at $\alpha = .01$ ($t = 4.398$). In this case the dual activity causes the constraint to appear less costly than it really is. The direction of the bias can again be explained by the tendency of the optimization to select options with optimistic production estimates.

The implications for solution feasibility of using stochastic production coefficients in constraints which can be rendered infeasible because of the errors in estimation are quite disturbing. Of the 30 simulation solutions, and with only one output constraint, 27 of the optimal solutions actually were not feasible. Underachievement of the timber goal was as high as 11 percent. This would imply that, in an average forest planning problem where time dynamics and many output constraints are included, there is nearly no chance that the resulting solution is truly feasible.

The tendency to select infeasible solutions can be explained by two factors. First, recall that, in the unconstrained model, positive errors in estimation of output quantities tended to be selected. This fact led to the conclusion that the results of LP models are optimistically biased when stochastic production coefficients are used. Second, because the model is required to

produce a specific amount of the output that is constrained, an added tendency to choose optimistic estimates is included.

Conclusions

In this paper two very different approaches to evaluate the impact of stochastic production coefficients in land allocation linear programs have been reviewed. The two approaches address very different research questions and employ methods totally dissimilar, but both reach the same conclusion; land allocation linear programs with stochastic production estimates are very unlikely to find feasible solutions as they are typically solved.

Another common conclusion from both papers is, unfortunately, that an approach that ameliorates this problem is not currently available. In fact, the two papers point out that it is not clear what the correct formulation for optimization with random production coefficients is in the first place. A good deal of further research is needed in this area, and in the meantime, caution is indicated when using LP in uncertain environments.

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Choice of Multicriterion Decision Making Model for Forest Watershed Resources Management

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Abstract.--An algorithm for selecting a multicriterion decision making (MCDM) technique for forest watershed resources management is modeled as a multicriterion problem. The procedure involves evaluation of feasible alternative MCDM techniques with respect to different sets of choice criteria. A particular technique is used to analyze the problem leading to a preference ranking of the alternative MCDM techniques.

The purpose of this paper is to present a procedure by which the most suitable MCDM technique can be selected for application to a multicriterion forest watershed resources management problem. Of explicit concern is the matching of a given multicriterion watershed resources management problem with an appropriate technique.

Considering the large number of techniques available, an applied analyst can get confused in determining which technique to choose when confronted with a real problem. Such ambiguity can cause inappropriate selection of a MCDM technique resulting in a misleading solution and wrong conclusions. For example, Cohon and Marks (1975), in their classification of MCDM techniques that can be used to solve water resources problems, stated that the ELECTRE method was not applicable to these problems. Krysztofowicz et al. (1977), however, stated the opposite by pointing out that ELECTRE was successfully applied to water resources problems and that its use in this area should be continued. The latter was further proven to be true in a subsequent study by Gershon et al. (1982). Given such apparent contradictions, it is not surprising to see a mismatch in practice between a real world problem and the MCDM technique applied to solve that particular problem.

There are four possible consequences of this kind of mismatch. First, as stated above, the solution resulting from poorly matched problem-MCDM technique situation will be misleading or unsatisfactum. Second, useful techniques may be judged inappropriately like that of ELECTRE in Cohon and Marks (1977), due to the poor results obtained, because they are applied incorrectly. Third, the mismatch subsequently results in wrong decisions incurring losses in valuable time, energy, and money. Finally, it may discourage potential users from applying MCDM techniques to real world problems. To avoid these kinds of problems, a procedure for selecting the "best" solution technique for a particular problem is presented in this paper.

The paradigm for selecting an appropriate MCDM technique for evaluating a multicriterion forest watershed resources management problem can be briefly described in terms of the following steps:

1. Defining the desired objectives or purposes that the MCDM techniques are to fulfill.
2. Selecting evaluation criteria that relate technique capabilities to objectives.
3. Listing and specifying MCDM techniques available for attaining the desired objectives, that is, solving multicriterion watershed management problems.
4. Determining technique capabilities or the levels of performance of a technique with respect to the evaluation criteria in solving a multicriterion problem.
5. Constructing an evaluation matrix (techniques versus criteria array), the elements of which represent the capabilities of alternative techniques in terms of the selected criteria (obtained in step 4).

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6. Analyzing the merits of the alternative MCDM techniques with respect to a given multicriterion forest watershed resources management problem and selecting the most satisficing technique.

Steps 1 through 5 constitute the multicriterion formulation procedure, while step 6 is the implementation of the MCDM technique selection procedure. The roles of these steps in the selection process, that is the steps of the technique selection algorithm, are described in the subsequent sections.

Background

The growth and diversification of MCDM techniques in recent years have been phenomenal. In spite of this, however, the applied practitioner, for a variety of reasons, has not used the techniques extensively. This problem of MCDM techniques not being implemented is well documented in the literature as shown in Evans (1984), Romero and Rehman (1987), Shannon (1975), and Zionts (1979) among others. One reason for this problem may be the lack of guidelines to match an appropriate technique to a particular real world problem, that is, there appears to be no framework general enough to guide practitioners in various fields in choosing an appropriate MCDM technique for application to multicriterion problem of their choice.

Criteria for Selecting MCDM Techniques

The selection of a MCDM technique for solving a multicriterion problem is dependent upon a set of selection criteria. Tecle (1988) identified 49 different criteria upon which the choice of an appropriate MCDM technique for a particular problem can be based. These criteria can be categorized into four groups depending on whether they describe mainly (1) the characteristics of the decision maker (DM) and/or analyst involved, (2) the characteristics of the algorithm for solution, (3) the characteristics of the problem under consideration, or (4) the nature of the obtainable final solution.

In this paper only 24 selection criteria are used for evaluating the appropriateness of a set of MCDM techniques to solve a forest watershed resources management problem. The limiting factor for utilizing only 24 criteria is the lack of adequate information on the actual use of the rest of the criteria to evaluate the performance of the techniques in solving such problems. The role of the 24 criteria in the evaluation process will be discussed later. In the meantime, a list of feasible MCDM techniques are provided from which the best technique for forest watershed resources management is selected.

Alternative MCDM Techniques

More than 70 MCDM techniques were identified in Tecle (1988). However, it would be very difficult if not impossible for any one individual to be skilled enough to apply all of those techniques, and experience in the use of a technique is a prerequisite for evaluating a techniques with respect to a set of criteria (Duckstein et al. 1982, Gershon 1981, Gershon and Duckstein 1984). With this idea in mind, only a few MCDM techniques are considered for evaluation in this study. These are the set of alternative techniques in table 1 with which the author has some familiarity. Here, they are evaluated for their suitability to solve a multicriterion forest watershed resources management problem such as the one described in Tecle (1988).

Evaluation of MCDM Techniques

In this section, a way of evaluating the performance of the alternative MCDM techniques under consideration is provided. This evaluation is made with respect to each of the four different groups of criteria, that is, DM/analyst-related criteria, technique-related criteria, problem-related criteria, and solution-related criteria, separately. This procedure lays the basis for the development of four evaluation matrices each of which consisting of techniques versus criteria array. The array elements are the evaluation scores of all the techniques with respect to each criteria in each criterion group. The level of these scores are based on the authors experiences in applying the techniques as well as the evaluation results of previous works such as those of Cohon and Marks (1975), Duckstein et al. (1982), Gershon (1981), Gershon and Duckstein (1984), Khairullah and Zionts (1979), Ozernoy (1987), and Rietveld (1980). The arrays so formed in turn provide the information necessary to achieve the desired choice of techniques.

Table 1.--Alternative MCDM techniques considered for selection.

1.	Analytic Hierarchy Process (AHP) (Saaty 1977, 1980)
2.	Composite Programming (CTP) (Bogardi and Bordassy 1983)
3.	Compromise Programming (CP) (Zeleny 1973, 1982)
4.	Cooperative Game Theory (CGT) (Nash 1953, Szidarovszky 1984)
5.	Displaced Ideal (DISID) (Zeleny 1974, Nijkamp 1979)
6.	ELECTRE (ELEC) (Benayoun et al. 1966, Roy 1968)
7.	Evaluation and Sensitivity Analysis Program (ESAP)
8.	Goal Programming (GP) (Charnes and Cooper 1961, Ignizio 1976)
9.	Multiattribute Utility Theory (MAUT) (Keeney and Raiffa 1976)
10.	Multicriterion Q-Analysis (MCQA) (Duckstein and Kempf 1979)
11.	Probabilistic Tradeoff Development Method (PROTR)
12.	Zionts-Wallenius (Z›W) (Zionts and Wallenius 1976)
13.	Step Method (STEM) (Benayoun et al. 1971)
14.	Surrogate Worth Trade›off (SWT) (Haimes and Hall 1974)
15.	PROMETHEE Method (PRM) (Brans and Vincke 1985)

After constructing the evaluation matrices consisting of alternative MCDM techniques versus criteria array, the DM's preference structure over the set of criteria in each matrix is determined to complete the problem formulation stage. Every criterion in any one of the four categories is assigned a weight relative to its importance in that group and also reflecting its significance with respect to the problem at hand. For example, when considering the technique-related criteria, ease of coding is weighted much higher than the "number of parameters required" in a technique. Based on the author's experience, it is more difficult to understand and use a technique characterized by coding complexity than one which requires a lot of parameters to apply, all other characteristics remaining the same. This is the reason for attributing the higher weight value to ease of coding than to the number of parameters required. In this paper, the criterion weights in each group are presented as part of the evaluation matrix corresponding to each criterion group. The process of constructing the evaluation matrices is described in the following subsections.

Evaluation Using DM or Analyst-Related Criteria

The DM or analyst-related criteria are those for which the MCDM techniques are evaluated with respect to the DM's or analyst's level of knowledge and willingness to use them. For evaluating the performances of MCDM techniques with respect to these criteria, the following questions can be asked:

1. How much knowledge is required of the DM to understand and use the techniques?
2. How much desire does the DM have for interaction?
3. How much of the DM's time does the technique require?
4. How much actual knowledge does the DM need to have to use the technique?
5. What level of skill does the analyst need to have to use the technique?

The responses to these questions can be made irrespective of the characteristics of the problem under consideration, that is, no knowledge of the problem is required to evaluate the techniques using this group of criteria. Evaluation with respect to these criteria is made using a subjective scale with a value ranging from one to ten, where one represents the worst extreme case, that is, a task the particular technique does not fulfill and ten indicates the best possible performances that can be attributed to the particular technique. In this manner the evaluation matrix of table 2 is constructed.

Evaluation Using Technique-Related Criteria

The technique dependent criteria are another group of characteristics for which the MCDM techniques can be evaluated without any knowledge of the problem upon which the techniques are to be applied. The techniques can be evaluated once by the analyst with respect to these criteria and the results of that evaluation can be used in all composite evaluation schemes involving different problems (Gershon and Duckstein 1984). The technique-related criteria used in this study are:

1. CPU time required by the technique.
2. Number of parameters required in using the technique.
3. Ease of using the technique.
4. Computational burden experienced in utilizing the technique.
5. Ability of the technique to get efficient points.
6. Ease of coding.

The evaluation of the MCDM techniques with respect to these criteria is made using a subjective scale similar to that utilized in the DM/analyst-related criteria case. Due to the subjective nature of such ratings, it is important for each analyst making use of MCDM techniques to construct his/her own table like that shown in table 3. This method was followed by Gershon (1981) and Gershon and Duckstein (1984) during the development of their model choice algorithm. Having used one MCDM technique many times, an analyst is certain to consider it "easy to use" due to his familiarity with it (Gershon 1981).

Table 2.--Evaluation matrix of techniques versus DM or analyst-related criteria.

		Alternative techniques														
Criteria	Weight	CP	CGT	CTP	GP	STEM	MAUT	ESAP	MCQA	ELEC	AHP	Z-W	PROTR	SWT	DISID	PRM
DM's level of knowledge	4	4	3	6	5	6	3	4	7	9	5	9	2	4	4	9
DM's desire to interface	3	9	9	10	8	5	7	8	9	8	6	3	2	5	5	8
Time avail. of DM	3	10	10	8	8	5	3	2	9	9	7	7	5	6	6	8
DM's actual knowledge	2	9	7	8	10	9	6	5	10	8	7	7	4	7	9	7
Analysts skill	1	10	9	8	7	6	7	6	4	3	6	6	7	5	8	6

Table 3.--Evaluation matrix of techniques versus technique-related criteria.

Criteria	Weight	Alternative techniques														
		CP	CGT	CTP	GP	STEM	MAUT	ESAP	MCQA	ELEC	AHP	Z-W	PROTR	SWT	DISID	PRM
CPU time required	3	6	4	4	7	7	4	3	8	10	6	7	7	4	5	8
No. of param required	2	9	9	7	7	6	8	7	4	5	7	7	6	5	9	7
Ease of use	4	8	7	6	8	1	9	7	9	7	7	8	8	2	6	8
Computational burden	4	6	5	7	7	7	4	4	9	8	8	7	5	2	6	7
Ability to get eff. points	5	8	9	9	1	5	8	6	6	4	5	8	8	10	7	4
Ease of coding	4	8	9	6	7	7	8	7	9	7	7	6	3	1	8	7

Evaluation Using Problem-Related Criteria

In order to employ some of the problem-related criteria for evaluation of the techniques, it must be asked if the particular technique can be applied to perform the following tasks in a forest watershed resources management problem. The tasks considered here relate the ability of the techniques to:

1. solve problems with non-numerical data.
2. choose from among a finite number of alternatives.
3. solve nonlinear problem.
4. handle a large scale problem.
5. handle an infinite number of alternatives.
6. solve a dynamic problem.
7. handle integer or mixed integer problem.

The multicriterion forest watershed resources management problem described in Tecle (1988) is considered for evaluating the performance of the individual alternative MCDM technique with respect to these seven criteria. Since the given problem can be solved in both discrete and continuous forms and since multicriterion forest watershed resources problems can be constructed using either numerical data or mixed data as shown in Tecle (1988) and Tecle et al. (1987), all the 15 MCDM techniques in table 1 are taken as feasible alternatives to solve a forest watershed resources management problem.

Evaluation of the applicability of the techniques with respect to the problem-related criteria is made using a "yes" or "no" response to the above seven tasks. But, the responses can be provided in the form of the binary numbers 0 and 1 as shown in table 4, where 0 stands for a no-response and 1 stands for a yes-response, for computational purposes. The types of responses are based on the author's experience in applying the techniques and evaluation of works of others as stated previously.

Evaluation Using Solution-Related Criteria

The preference of one MCDM technique over another is also a function of the nature of the solution to be obtained using the techniques for the particular problem under consideration. The nature of the solution may be described by its uniqueness, reliability, and efficiency among others. Given such solution characteristics, all the feasible techniques can be assessed from the solutions obtained in their past applications to specific real-world problems or they can be applied to the particular problem under consideration and then compare the solutions obtained with each other in terms of a set of solution-related criteria. The following solution-related criteria are used to evaluate the MCDM techniques in this study:

1. Consistency of solutions obtained.
2. Robustness of results with respect to changes in the values of parameters.
3. Usefulness of the solutions to the DM.

Table 4.--Evaluation matrix of techniques versus problem-related criteria.

Criteria	Weight	Alternative techniques														
		CP	CGT	CTP	GP	STEM	MAUT	ESAP	MCQA	ELEC	AHP	Z-W	PROTR	SWT	DISID	PRM
Handle qual. data	5	1	1	1	0	0	1	1	1	1	1	0	0	0	1	1
Finite no. of altern.	4	1	1	1	0	0	1	1	1	1	1	1	0	0	1	1
Non-linear problem	3	1	1	1	1	1	0	0	0	0	1	0	1	1	1	0
Problem size	3	1	1	1	1	1	0	0	1	1	1	1	0	0	1	1
Infinite no. of altern.	4	1	1	1	1	1	1	1	0	0	0	1	1	1	1	0
Dynamic problem	3	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Handle integer	2	1	1	1	1	0	1	1	1	1	1	0	0	0	0	1

Table 5.--Evaluation matrix of techniques versus solution-related criteria.

Criteria	Weight	Alternative techniques														
		CP	CGT	CTP	GP	STEM	MAUT	ESAP	MCQA	ELEC	AHP	Z-W	PROTR	SWT	DISID	PRM
Consistency of results	2	8	6	9	7	8	10	7	4	5	7	5	9	10	8	4
Robustness of results	2	8	6	9	7	7	8	7	8	9	6	6	7	6	9	7
Usefulness of results of DM	3	6	7	8	5	6	9	8	8	8	6	9	8	7	7	6
Confidence of results	3	7	6	8	5	5	3	3	6	5	5	7	6	5	6	6
Strength of eff. sol.	1	7	9	7	2	5	4	4	3	4	5	4	5	6	2	3
No. of sol. in each altern.	1	9	5	7	9	7	7	6	3	4	6	6	7	8	8	4

4. DM's confidence on the results obtained.
5. Strength of the efficient solution.
6. Number of solutions occurring in each iteration during the solution process.

Much as in the other criterion groups, the evaluation of the techniques with respect to this group of criteria is also made using subjective scales. The range of the scale values is similar to that in the first two cases. Unlike in the latter cases, however, knowledge of the problem and a good idea about its anticipated possible solution are required to evaluate a technique in this one. The evaluation scores of table 5 are, therefore, determined from actual applications of the techniques to multicriterion forest watershed resources management problems made at different times by such researchers as Bardossy et al. (1985), Goicoechea et al. (1976), Khalili (1986), Tecle (1987), and Tecle et al. (1987). Other helpful information for evaluation was also obtained from various studies on related resources management problems such as those pointed out at the beginning of this section.

Solving the MCDM Technique Selection Problem

The different sequential steps taken during a multicriterion decision making process can be lumped into two complementary stages: the problem formulation stage and the problem solution stage. The problem formulation stage which includes the activities described in the four parts of the above section culminates in the formation of the evaluation matrices. The problem solution stage, on the other hand, constitutes the application of a MCDM technique on the matrices to determine the desired solution. According to Wymore (1976), the problem formulation stage is as important, if not more important, than the solution stage. This is particularly true for problems concerning large scale systems where, at least partly, the manner in which the problem is formulated helps in determining the most suitable MCDM technique to use (Gershon and Duckstein 1984).

The objective of the technique selection algorithm is to select the most appropriate MCDM technique for solving a forest watershed resources management problem from among the given set of feasible alternative techniques. The constructed evaluation matrices of the technique choice problem partly provide the information needed to make the choice of a technique. The other part comes with the application of a selection algorithm on these evaluation matrices.

Now, since the problem of selecting MCDM techniques is itself a multicriterion problem, the MCDM technique selection algorithm can be applied to select the technique for this purpose also. But as Gershon and Duckstein (1984) pointed out, this procedure would lead to a cyclical process. To avoid this problem, a technique must be arbitrarily chosen and applied on the MCDM choice evaluation matrices to select the most satisficing technique for the problem at hand. This choice, however, must take into account the type of the problem to be solved. In this case, for example, since the MCDM technique selection problem is defined by a discrete set of systems and must be analyzed in two levels that consist of (1) solving each evaluation matrix separately and then (2) combining the results obtained to form a new evaluation matrix from which the final compromise solution is determined, the technique choice cannot be just arbitrary. This is because the discrete formulation and the two-level solution procedure requirements of the problem limit the selection of the choice algorithm.

The algorithm which fulfills this requirement and is used for the purpose of selecting the best MCDM technique is composite programming (CTP) (Tecle 1988). This algorithm is an extension of compromise programming (Bardossy et al. 1985) and is adapted here to perform the two level trade-off analysis required in the technique choice problem. In the first level, different L_p-norms are applied to seek a compromise within each of the four criterion groups and then a different L_p-norm is applied to make a trade-off among these four groups to arrive at the final preference ranking of the alternative MCDM techniques under consideration.

Discussion of Results

The solution to the MCDM technique selection problem is obtained in terms of a L_p-distance from an ideal point. The ideal point in this case is considered to be the point consisting of the highest criterion score in each row of the evaluation matrix.

Since composite programming algorithm was used to solve the problem, the results for the two levels of analysis are presented at first. Table 6 represents the compromise solutions corresponding to the four evaluation matrices of tables 2 through 5.

It is interesting to note in table 6 that the preference ranking of the alternative techniques differ from one criterion group to the other. If the status of ELECTRE is examined, for example, it is observed to be ranked first when evaluated using the DM/analyst-related group of criteria but falls to ninth, fourth, and tenth ranks when evaluated using the problem, technique, and solution-related groups of criteria, respectively. There are at least two good reasons for this phenomenon.

One reason could be due to biases attributable to the way the subjective performance evaluation scores are obtained and the method of assigning the criterion weights and other parameters used. The performance evaluation scores were determined on the bases of the experiences of individuals in using the techniques while the criterion weights and the other parameters are meant to represent the DM's preference structure and the effect of the criterion score magnitude, respectively. Among the techniques considered, ELECTRE is one of the most widely used techniques. This is particularly true when the European experience with MCDM is taken into consideration.

The other reason is due to the fact that the different criterion groups evaluate quite different characteristics of the techniques. The ranking within each group is a function of the manner the performance of the technique in solving a particular problem is evaluated with respect to the criteria in that group. Since ELECTRE is taken to represent all four ELECTRE types, the evaluation scores used are representative of the average performance levels of all four types. Besides, there are some

Table 6.--Compromise ranking of alternatives and their respective L_p-distance.

	Criteria groups							
	DM/analyst		Technique		Problem		Solution	
Alts.	Value	rank	Value	rank	Value	rank	Value	Rank
CP	2.340	4	2.855	1	0.000	1	5.117	7
CGT	3.594	10	4.818	5	3.000	2	5.147	8
CTP	3.042	6	6.031	7	0.000	1	0.584	1
GP	2.556	5	11.413	14	7.071	8	9.831	15
STEM	3.226	8	9.580	13	7.348	9	6.287	10
MAUT	4.677	14	6.472	9	5.196	5	9.019	13
ESAP	4.564	13	7.988	12	5.196	5	9.256	14
MCQA	1.524	2	4.428	3	5.831	6	4.472	5
ELEC	1.465	1	6.582	10	5.831	6	4.375	4
AHP	3.173	7	5.401	6	5.000	4	7.295	12
Z-W	3.285	9	3.000	2	6.856	7	4.903	6
PROTR	5.718	15	6.655	11	7.937	10	2.367	2
SWT	3.929	12	13.855	15	7.937	10	5.618	9
DISID	3.758	11	4.797	4	3.606	3	2.887	3
PRM	1.938	3	6.387	8	5.831	6	6.910	11

Table 7.--Final overall ranking of alternatives for a particular inter-criterion group trade-off parameters.

Technique	Distance value	Rank
Compromise programming	3.0074	1
Composite programming	3.9427	2
Displaced ideal	4.0227	3
Cooperative game theory	4.3099	4
Multicriterion q-analysis	4.7194	5
Zionts-Wallenius method	4.8567	6
Analytic hierarchy process	5.5514	7
ELECTRE methods	5.6188	8
PROMETHEE methods	6.0370	9
Probabilistic trade-off development method	6.4037	10
Multiattribute utility theory	6.5810	11
Evaluation and sensitivity analysis program	7.2692	12
Step method	7.8649	13
Goal programming	9.3320	14
Surrogate worth trade-off method	10.1758	15

limitations to its use. It can only be applied to discrete problems that have finite numbers of alternatives (Duckstein and Bogardi 1987). It is no wonder then to see ELECTRE having very low preference ranking, tenth, when evaluated with respect to the solution-related criteria.

The discrepancies in the rankings of the other alternatives with respect to the different groups of criteria can be explained similarly. But since our interest is in the final preference ranking, the results of the second level of evaluation become more important. These results are shown in table 7 where the overall preference rankings and the associated L_p-distances of the alternatives under consideration are determined.

Of the 15 techniques examined, compromise programming (CP), composite programming (CTP), the method of the displaced ideal, and cooperative game theory in that order are found to be the most preferred techniques. Since all of these techniques are of the distance-based type, the concept of distance may have helped to make these techniques be easily understood and become popular. The reason for their high ranking, however, is much more than that and may be explained by looking back at the results of the first stage of evaluation in table 6.

All four techniques are highly rated with respect to the problem-related criteria as shown in the sixth and seventh columns of table 6. These techniques can handle all the tasks ascribed by this group of criteria except the task of directly solving problems having non-numerical data. Problems of the latter type are usually handled by a heuristic scaling procedure which consists of converting the data into numerical form (Gershon et al. 1982, Tecle 1986, Tecle et al. 1987a).

The situation, however, is quite different when the techniques are evaluated with respect to the other criterion groups. With respect to the DM/analyst criterion group, compromise programming and composite programming are ranked fourth and sixth while cooperative game theory (CGT) and the method of the displaced ideal fall to the tenth and eleventh ranks,

respectively. The reason for this is that CGT and the method of the displaced ideal are rated low with respect to some of the criteria in this group. Both techniques, for example, require the DM to have some knowledge of utility theory, the concepts of the ideal point, in the displaced ideal, and status quo point in the case of CGT and some axioms to understand and use the techniques (Szidarovszky et al. 1978, 1984; Zeleny 1982).

For this reason their evaluations with respect to the "level of knowledge required of the DM" criterion have low evaluation scores as shown in column 2 of table 2. Other factors contributing to the low ranking of these alternatives are the levels of the criterion weights and trade off parameters assigned to each criterion. As shown in table 2, the "level of knowledge required of the DM" is given the highest weight in the group. This supplements the criterion scores in determining the ranking of the alternatives. An alternative having a high evaluation score with respect to an important criterion (that is, one with high criterion weight) will be ranked high. Conversely, if an alternative is rated low with respect to an important criterion, that alternative will have a low rank. The latter contributes to the low ranking of CGT and the method of the displaced ideal with respect to the DM/analyst-related criteria shown in columns 2 and 3 of table 6. Similar reasoning can be given to the average ranking of CTP with respect to the technique-related criteria and CP and CGT with respect to the solution-related criteria (table 6).

There is also lack of consistency in the ranks of the lowest ranked alternatives across the criterion groups. Goal programming which is ranked fourteenth overall, for example, is ranked fairly high (fifth) with respect to the DM/analyst-related criteria, average with respect to the problem-related criteria and very low with respect to both technique-related (fourteenth) and solution-related (fifteenth) criteria. The concept of GP is easily understood and the technique is widely accepted for real-world application; for these reasons it is determined to be ranked above average with respect to the DM/analyst-related criteria. GP is, however, ranked eighth with respect to problem-related criteria because of its inability to handle dynamic problems as well as problems with finite number of alternatives and non-numerical data. Likewise GP is ranked very low with respect to both the technique-related and the solution-related groups of criteria. This low ranking is mainly due to its inability to get the efficient point of a multicriterion problem. Because the technique, practically solves the problems as single objective functions, that is, minimizing the sum of the deviation of the objective function values from a goal point, it cannot in its original version produce a strongly efficient solution that simultaneously satisfies the different objectives. Besides, some of the solution points in GP may be dominated points. Note that the consideration of a modified GP algorithm, a direction-based one (projecting the current point on the Pareto optimum) would alleviate this problem.

The reasons for the other low ranking alternatives can be similarly explained as well. Other factors that contribute to the ranking level of alternatives are the range of the values of the parameters used during the two-level evaluation scheme (Tecle 1988).

Conclusions

A forest watershed resources management problem is considered to be inherently a multicriterion problem that needs to be analyzed using MCDM techniques in order to arrive at a satisficing management scheme. Since there are more than 70 different kinds of MCDM techniques available, a choice of the most appropriate technique for application to a forest watershed resources management problem is important.

In this study, an algorithm has been developed for selecting from among a set of feasible MCDM techniques, the most appropriate technique for application. The algorithm is based on a first level evaluation of the techniques with respect to four different groups of criteria: (a) DM/analyst-related, (b) technique-related, (c) problem-related, and (d) solution-related criteria, resulting in the ranking of the techniques with respect to each criterion-group. Then an overall ranking of the techniques, can be arrived, in a second stage through a linear combination of the results in the first stage.

It is determined from the results that it is not appropriate to select one MCDM technique as the best for a given DM/analyst, or a given problem or for a particular solution desired. Rather, a technique can only be considered best when it is determined to be preferred through a combination of the effects of these components and the characteristics of the technique itself. In this fashion, the MCDM technique choice algorithm used in this study shows compromise programming and composite programming to be the most preferred techniques while surrogate worth trade-off method and ordinary goal programming are determined to be the least preferred ones for a forest watershed resources management problem such as the one described in Tecle (1988). The other techniques are ranked in-between these extreme rankings.

As a final remark, it should be pointed out that the MCDM technique choice algorithm discussed in this paper can be applied not only for selecting MCDM techniques to solve other MCDM problems natural resources management problems, but also to any kind of MCDM technique choice problems. To be universally and efficiently useful, however, the MCDM technique selection algorithm should be developed to include all available techniques as candidates for the selection process. In this respect extensive research on the relative performances of the techniques in solving a particular problem should be made. The technique selection algorithm can also be applied to more problems of the same type to test the effect of the analyst's bias on the choice. Lastly the technique selection algorithm should be made general enough to be applied to different types of problems. The aim should be toward the development of a handy MCDM choice algorithm for matching a particular MCDM technique to any real world multicriterion problem.

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Multiobjective Forest Management: A Visual, Interactive, and Fuzzy Approach

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Abstract.--A multiobjective forest watershed resources management problem with fuzziness is formulated and then analyzed using a free search type of interactive procedure, PARETO RACE. The system enables the decision-maker to search freely any part of the efficient frontier by controlling the speed and direction of motion until an acceptable compromise solution is reached.

In this paper, a visual "free search" type of interactive multicriterion linear programming technique is applied to the management of forest watershed resources. The approach which requires no assumption on the decision maker's (DM) value function is illustrated by means of a forest watershed management experimental pilot project in the ponderosa pine forest part of the 275,000 acres Beaver Creek watershed in the Salt-Verde Basin of Arizona. There are 1,650,000 acres of ponderosa pine forest in the Basin as a whole. Based on climate and physiographic conditions (Beschta 1976, Carder 1977, Ffolliott et al. 1972), the ponderosa pine forest in this Basin can be considered as representative of the 4,282,000 acres and 11 million acres of ponderosa pine forest in the whole of Arizona and the entire southwestern United States, respectively (U.S. Forest Service 1977).

In the experimental study, alternative forest watershed schemes were carefully designed and executed to assess the range of biophysical and socio-economic effects of management practices, with the goal of selecting those practices that are likely to give the most desirable mix of benefits.

For the purposes of this study, the benefits were grouped into six objective functions, as described below; also, the results of a 5-year study from six pilot watersheds has been used for MCDM model calibration. In general, forest watersheds utilize a set of resources including land, water and labor to produce a set of goods and services such as water, herbage for animal forage, timber and recreation, and also some adverse consequences like sediment yield. In the present decision formulation, let x be an alternative decision vector and $\{z_i(x):i=1,...,I\}$ an objective function vector; then a balanced or compromise policy, also called a "satisfactum," is an acceptable trade-off between the conflicting objective functions $z_i(x)$. The problem is also subject to physical constraints, some of which are fuzzy. For instance, the total area that may be subject to high percentage basal area removal is not precisely defined. Further, an objective function such as recreation may not necessarily be maximized or minimized, but it may be specified as a fuzzy goal.

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Background

Forest watershed management is multiobjective in nature. Thus, the U.S. Department of Agriculture, Forest Service is required by law to produce alternative plans that provide the multiple use and sustained yield of goods and services from the National Forest System in a way that maximizes long-term net public benefits in an environmentally sound manner (U.S. Forest Service 1982). A moderate number of MCDM analyses of forest watershed management schemes may be found in the literature, being usually linear numerical objective functions and linear constraints, mostly of the goal programming type (Arp and Levigne 1982, de Kluyver et al. 1980, Field 1973, Goicoechea et al. 1976, Mattheiss and Land 1984, Schuler et al. 1977, Smith and Theberge 1987, Steuer and Schuler 1978). However, fuzziness has generally not been considered.

On the other hand, several approaches have been proposed to find an optimal compromise solution to a multiple objective decision problem using fuzzy set theory (Baas and Kwakernaak 1977; Bardossy et al. 1987; Bogardi et al. 1983; Chanas and Florkiewicz 1987; Nachtnebel et al. 1986; Orlovsky 1984; Sakawa 1983; Sakawa and Yano 1985; Sakawa et al. 1987; Siskos et al. 1984; Yager 1978; Yu 1984; Zimmermann 1978, 1984). The above approaches possess a common drawback: the

DM can include soft information into the model but cannot softly analyze the set of possible solutions; every time the meaning of softness must be specified *a priori* and then the technique produces a unique "hard" (so-called) fuzzy decision, without intervention of the DM. This paper attempts to develop a general approach for dealing with objectives and constraints in either a "hard" or a "soft" way, or both ways simultaneously. Fuzziness is like an objective, which may be controlled during the process. The DM can consider multiple objectives and at the same time operate with fuzzy concepts. The approach helps the DM see the impact of fuzziness on the solutions, instead of generating a unique solution.

Problem Formulation

A description of the Beaver Creek forest watershed experimental study is given in Baker (1986), Brown et al. (1974), and the U.S. Forest Service (1977), and an MCDM problem formulation thereof is presented in Tecle (1987, 1988). PARETO RACE is described in Korhonen and Wallenius (1987).

The present paper thus focuses on the fuzzy MCDM formulation and analysis. Specifically, six single period linear objective functions along with two physical (land) constraints are constructed to yield a model adapted for analysis by multiobjective linear programming. The decision variables are the size of tree basal area removal as percent (%) of total forest area as follows:

x_1 = untreated forest land (no-action option)

x_2 = forest land treated with regular 1/3 stripcut

x_3 = forest land treated with irregular 1/3 stripcut plus thinning to make an overall 50% tree basal area

x_4 = forest land treated with irregular 1/2 stripcut plus thinning to leave an overall 35% tree basal area

x_5 = forest land thinned to 25% of original tree basal area

x_6 = forest land 100% tree basal area removed.

The six objective functions are concerned with the extent of application of forest treatments for purposes of, respectively: (1) increasing water runoff on the Salt-Verde River Basin (abbreviated W. Yield in the model), (2) improving herbage production both for wildlife and livestock use (Herb. Prod.), (3) reducing sediment yield (Sed. Yield), (4) maintaining recreational benefits (Rec. Use), (5) improving economic benefits (Ec. Benef.), and (6) reducing operational cost (Oper. Cost). The problem is described by the following noncommensurable objective functions expressed in the indicated units per acre:

1. Maximize water runoff: $z_1 = \Sigma w_j x_j$, $j = 1,...,6$,

   w_j = runoff (in acre-ft).

2. Maximize herbage production: $z_2 = \Sigma f_j x_j$,

   f_j = herbage production (in lbs/acre).

3. Minimize sediment yield: $z_3 = \Sigma s_j x_j$,

   s_j = sediment yield (in tons/acre).

4. Maintain recreational use level: $z_4 = \Sigma r_j x_j$,

   r_j = recreation visitor-days in one year (RVD/acre/yr).

5. Maximize economic benefit: $z_5 = \Sigma b_j x_j$,

   b_j = return (in dollars).

6. Minimize operational cost: $z_6 = \Sigma c_j x_j$,

   c_j = expenditure (in dollars).

Each coefficient in objective function 5 is the sum of per acre dollar values of timber production, livestock production, and water yield. There are also other economic benefits that can be obtained from forested watersheds, but it is difficult to determine their monetary values at this time.

Objective function 4 is neither minimized nor maximized. "Maintaining" means that a certain aspiration is specified for the objective level, which is to be achieved as closely as possible provided that it does not cause unacceptably large losses in the other objective function values. In fact, this type of imprecise preference function may be modelled as a L-R fuzzy set membership function (Dubois and Prade 1980).

The coefficient values are given in table 1.

The problem is subject to two physical constraints. First, the whole ponderosa pine forested area in the Salt-Verde Basin is considered for treatment; hence:

$\Sigma_j x_j = 1.00$ the available ponderosa pine forest in the Salt-Verde Basin. The available 1,650,000 acres are taken as unity.

Second, a restriction is placed on the maximum size of ponderosa pine forested land (AM) subjected to 100% tree basal area removal. However, this constraint usually cannot be specified precisely: only a range of acceptable values can be given. If it is further assumed that the DM has a monotonically decreasing preference for increasing values of AM, varying from a fully acceptable value of AM (> 358,000 acres) to a non-acceptable value of 424,000 acres. The proportions of these values to the total available area (1,650,000 acres) are equal, respectively, to .217 and .257. This yields, for the fully acceptable value of AM, the following constraint:

$3x_5 + x_6 \leq .217$ fully acceptable level of AM. (Maximum acreage of forested land with 100% tree basal area removed or severely thinned to 25% of original tree basal area.)

Note that the proportions of AM between fully acceptable (.217) and non-acceptable (.257) are taken into account by defining a proper fuzzy set membership function.

Approach

Imprecision in the elements of the problem is modelled using fuzzy set theory. Specifically, there are two fuzzy elements in

Table 1.--Objective function coefficients.

Objective functions z_i, i = 1,2,...,6		Type of treatment, j = 1,2,...,6					
		1	2	3	4	5	6
Water yield	(w)	3.782	4.284	4.840	5.360	5.650	5.950
Herbage prod.	(f)	10.20	188.63	203.61	285.90	414.66	1153.17
Sediment yield	(s)	0.118	2.810	3.890	4.920	5.610	7.460
Recreational use	(r)	1.387	1.618	1.202	1.090	1.020	0.809
Economic benefit	(b)	1644	1777	3147	3225	3273	16
Operational cost	(c)	0.0	146.130	196.12	228.84	244.27	260.20

the model, for which two different types of fuzzy set membership functions may be defined.

The first imprecise feature concerns "maintaining recreational use level." Here the DM specifies an "ideal" value of recreational use level (d_r) allowing, however, either underachievement or overachievement to some extent; that is, recreational use level is modelled as follows:

$$z_4 = \Sigma r_j x_j \cong d_r$$

The DM specifies 1.4 as an ideal value for d_r and also that values in the interval [0.8,1.8] may be acceptable. This information is used to define a triangular fuzzy set membership function as sketched in figure 1. This is a special case of L-R membership function (Dubois and Prade 1980).

The above functional form of $\mu(r)$ leads to introducing the two additional technical constraints into the model:

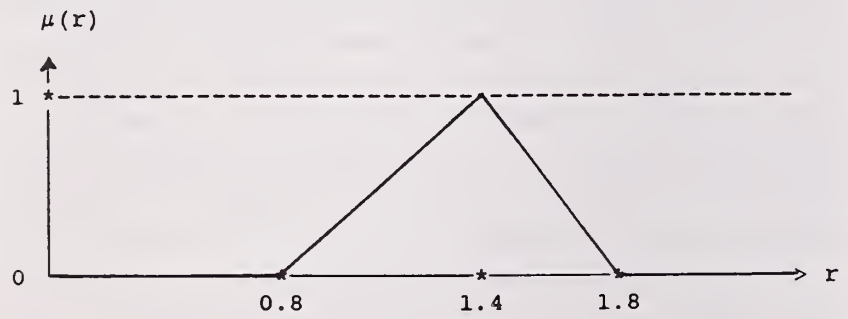


Figure 1.--Membership function of recreational use level (r).

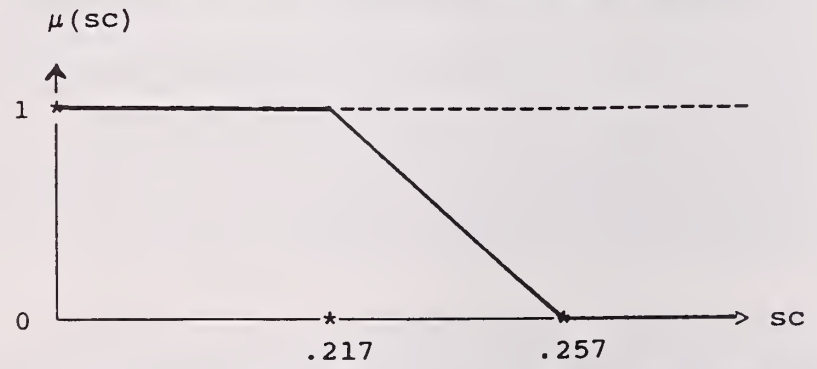


Figure 2.--Membership function of percentage area with maximum basal area removal (sc).

$$z_4 = \Sigma r_j x_j \leq 1.8 - 0.4\,\mu_r$$
$$z_4 = \Sigma r_j x_j \geq 0.8 + 0.6\,\mu_r$$

in which μ_r; $\mu_r \in [0,1]$, is now considered as a decision variable to be maximized.

The second imprecise feature introduced earlier dealt with the maximum forest acreage (AM) to be 100% tree basal area removed or severely thinned. Here, values below .217 are fully acceptable, whereas values above .257 are non-acceptable. These values are used to define a linear monotone nonincreasing membership function as sketched in figure 2.

Because of the monotone type of membership function corresponding to this constraint, one only needs to introduce into the model the following modification of the original constraint:

$$3x_5 + x_6 \leq .257 - 0.04\,\mu_{sc},$$

in which μ_{sc}; $\mu_{sc} \in [0,1]$, is taken as a decision variable to be maximized.

The final model formulation is:

$$\text{mx } z_1 = \Sigma w_j x_j$$
$$\text{max } z_2 = \Sigma f_j x_j$$
$$\text{min } z_3 = \Sigma s_j x_j$$
$$\text{max } z_5 = \Sigma b_j x_j$$
$$\text{min } z_6 = \Sigma c_j x_j$$
$$\text{max } \mu_r$$
$$\text{max } \mu_{sc}$$

subject to

$$\Sigma x_j = 1$$
$$\Sigma r_j x_j - 0.6\mu_r \geq 0.8$$
$$\Sigma r_j x_j + 0.4\mu_r \leq 1.8$$
$$(0,0,0,0,3,1)x + 0.04\mu_{sc} \leq .257$$
$$x \geq 0 \text{ and } x \leq 1$$
$$\mu_r \in [0,1]$$
$$\mu_{sc} \in [0,1]$$

Next, a brief introduction to PARETO RACE is provided, and the above model is analyzed.

The PARETO RACE Approach and Application

PARETO RACE (Korhonen and Wallenius 1987) represents a dynamic, visual, and interactive procedure for multiple objective linear programming. In PARETO RACE, a DM can freely search the efficient frontier of a multiple objective linear programming problem. Specific keys are used to control the speed and direction of motion. On a display, the DM sees the objective function values in a numeric form and as bar graphs whose length is dynamically changing along the efficient frontier. The keyboard controls include gears, an accelerator, brakes, and a steering mechanism, as described in appendix 1, for easy visual interaction. The program has been initiated after the developments in Korhonen and Laakso (1986a, 1986b). The DM controls PARETO RACE by using function keys as described in Korhonen and Wallenius (1987) and explained in appendix 1. To implement PARETO RACE, an IBM/PC1 microcomputer software package called VIG (Visual Interactive Goal programming) has been developed (Korhonen 1987). The current version of the program is capable of solving problems with a maximum of 96 variables and 100 rows; up to ten rows can be objectives. Using VIG the DM can consider the problem on hand in an evolutionary way; that is, the bounds of the constraints can be modified and the role of the objective functions and constraints can be interchanged during the interactive solution process. Furthermore, intermediate solutions can be stored, and values of rows and decision variables can be viewed on the screen; thus the DM proceeds in a progressive way towards a "satisfactum." If such a "satisfactum" is not reached, the DM can return to the beginning stage and reconsider the aspiration levels of objectives and constraints, or define a new set of objectives. PARETO RACE can be rerun as many times as necessary. Further details on VIG are found in Korhonen (1987).

The application is organized in three parts. First, an approach to arrive at a perception of the problem structure is described. Second, an important objective (here, economic benefit) is selected and a trade-off between this objective and fuzziness is analyzed. Third, a PARETO RACE including all objectives and fuzziness is iteratively run until a "satisfactum" may be reached.

Perception of the Problem Structure

In Korhonen (1987), the DM becomes acquainted with the problem structure by first stating an aspiration level vector and then proceeding to a consistency check. An alternative approach used in this paper consists of calculating the pay-off matrix and the corresponding decision vectors as shown in table 2.

In table 2, the following observations may be made by the DM:

- ✦ if the range of variation of an objective z_i is not large, each of the other objectives can likely be optimized at a very low "cost" to z_i,

Table 2.-- Pay-off matrix and corresponding decision vectors ($\mu(r) = \mu(sc) = 1$; * refers to the optimal objective function).

Pay-off matrix:		Pay-off and decision vectors				
		1	2	3	4	5
W. Yield	≥	4.737*	4.729	4.002	4.614	4.002
Herb. Prod.	≥	237.2	405.8*	70.00	211.3	70.00
Sed. Yield	≤	3.711	3.989	.9761*	3.466	.9761
Ec. Benef.	≥	2364	1511	1785	2461*	1785
Oper. Cost	≤	180.7	177.7	42.71	174.3	42.71*
Decision vectors:						
X(1)		--	--	0.7565	--	0.7565
X(2)		0.5967	0.7026	0.1712	0.5076	0.1712
X(3)		--	--	--	0.4201	--
X(4)		0.3310	0.0804	--	--	--
X(5)		0.0723	--	0.0723	0.0723	0.0723
X(6)		--	0.2170	--	--	--

- ✦ if two vectors in the pay-off matrix are identical, such as columns 3 and 5, or almost identical, then the objectives are likely to behave similarly in the neighborhood of the marginal solutions,
- ✦ if some decision variable appears often in the decision vectors subtable, such as X(2) or X(5), this variable is likely to be present in the solution point corresponding to a "satisfactum."

Furthermore, a DM not familiar with standard features of linear programming may note that every decision vector has three non-zero components (corresponding to the common set of constraints), and that X(5) and X(6) are not non-zero simultaneously (because they appear in the same linear constraint).

If the "worst" values for objectives are too optimistic, PARETO RACE will automatically update the initial ranges when needed.

Trading off one Objective Versus Fuzziness

Consider, for example, the interdependence between economic benefit and fuzziness. To investigate this we determine the fixed aspiration levels for other objectives (water yield ≥ 4.1, herbage production ≤ 300, sediment yield ≤ 3, and operational cost ≤ 130) and consider trade-offs between $\mu(r)$ and economic benefit with different values of $\mu(sc)$. The solution values at points of basis changes are given in table 3, where values of $\mu(r)$ smaller than 0.67 (in the last column) have no influence on the solution. Other solution values may be obtained by linear interpolation.

Table 3 shows that economic benefit does not appear to be very sensitive to the fuzzy parameter $\mu(sc)$. In contrast, this benefit is strongly influenced by the fuzzy function $\mu(r)$: in fact, as $\mu(r)$:0 1, the benefit function takes on roughly 42% of the

Table 3.--Sensitivity of economic benefit to fuzziness.

μ(sc)		μ(r) and solution values		
1.00	Ec. Benef.	1548.7	1785.8	1950.6
	μ(r)	1.0000	0.8215	0.6743
0.75	Ec. Benef.	1549.6	1782.1	1951.2
	μ(r)	1.0000	0.8250	0.6739
0.50	Ec. Benef.	1550.6	1778.4	1951.8
	μ(r)	1.0000	0.8285	0.6736
0.25	Ec. Benef.	1551.5	1774.6	1952.4
	μ(r)	1.0000	0.8320	0.6732
0.00	Ec. Benef.	1552.4	1770.9	1953.0
	μ(r)	1.0000	0.8355	0.6728

variation shown in the pay-off matrix (table 2). It means that letting recreational use stay at its ideal level is rather costly from the economic benefit point of view. In addition, the bound for sediment yield is binding after the first basis changes, and operational cost is not binding anymore after the second basis change. Obviously, herbage production is critical in trying to improve economic benefit. A broader perspective will now be sought by considering all objectives simultaneously.

Complete PARETO RACE

Now all "actual" objectives and fuzzy parameters--also taken as objectives--are considered and the subspace of reasonable solutions examined by using PARETO RACE. Figure 3 shows a sample solution and table 4 gives a set of five reasonable solutions; each of these solutions may be selected as a satisfactum by the DM.

From table 4, we see that variables X(1), X(5), and X(6) are present in all solutions. The presence of other variables depends on how much relative emphasis is placed on each of the six objectives.

Discussion and Conclusions

This investigation follows an interactive visual approach to trading off conflicting objectives, as recommended in Loucks

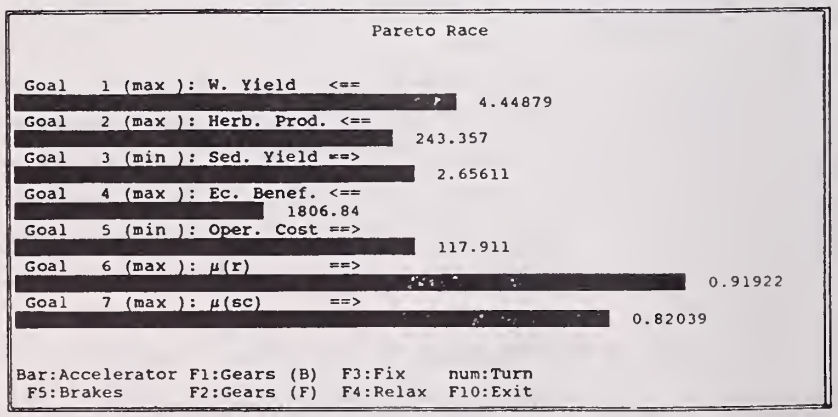


Figure 3.--An example of PARETO RACE screen.

Table 4.--A set of possible compromise solutions determined using PARETO RACE.

	Payoff and decision vectors				
	1	2	3	4	5
W. Yield	4.465	4.588	4.598	4.581	4.349
Frg. Prod.	300.0	309.0	303.9	264.1	199.1
Sed. Yield	2.942	3.041	2.934	2.651	2.041
Ec. Benef.	1549	1821	1882	1882	1882
Oper. Cost	130.0	130.0	122.4	107.0	84.61
μ(r)	1.000	.7600	.6748	.6854	.7732
μ(sc)	1.000	.7600	.4925	.0000	.0000
Rec. Use	1.400	1.257	1.206	1.211	1.264
Max. Rem.	0.217	0.227	0.237	0.257	0.257
Decision Vectors:					
X(1)	0.2622	0.3621	0.4422	0.5549	0.6165
X(2)	0.5178	0.1519	--	--	--
X(3)	0.0417	0.2878	0.3505	--	0.2246
X(4)	--	--	--	0.2623	--
X(5)	0.0194	0.0142	0.0150	0.0371	0.0490
X(6)	0.1588	0.1840	0.1923	0.1457	0.1099

and Fedra (1987), and illustrated in, for example, Okada et al. (1985). Specifically, here, forest watershed management has been formulated as a multiple objective linear programming problem; imprecision in either an objective function or a constraint has been introduced into the model by using fuzzy set membership function μ as a variable to be maximized, as suggested in Korhonen et al. (1987a). In order to trade off objective function values and μ, a "free" search type of interactive method called PARETO RACE has been applied. The advantages of such an approach are that:

- ✦ no value function needs to be elicited from the DM,
- ✦ no norm (such as an L_p-norm) needs to be defined,
- ✦ no aggregation rule for membership functions needs to be specified.

The disadvantage of such an approach is inherent to all unstructured MCDM-techniques; namely, that the rate of convergence toward a "satisfactum" cannot be guaranteed. This problem is discussed in Korhonen et al. (1987b), where DM's were sometimes observed to consider the same alternatives as best repeatedly but in any case stopped the search process very quickly.

The novelty in the present approach is an evolutionary viewpoint consisting of the following three steps:

1. acquiring a perception of the structure of the model to facilitate subsequent interactive analysis,
2. trading off one important objective at a time with one or more measures of imprecision,
3. proceeding to a complete analysis to obtain an overall view of the decision problem and to arrive at a "satisfactum."

Step 1 points out to the DM which decision variables are important and how the objective functions are related. This step may also provide a tutorial on certain properties of linear programming.

Step 2 gives a view on the sensitivity of important objectives to fuzzy elements of the model. Thus, in the case study, the economic objective exhibits substantial sensitivity to fuzzy membership function $\mu(r)$ representing acceptability of maintaining a given recreational use level. In contrast, this economic objective function exhibits very little sensitivity to $\mu(sc)$ representing acceptability of maximum area that may be subject to high percentage tree basal area removal.

Finally, step 3 provides a combined "hard" and "soft" analysis of the complete problem, and yields a set of reasonable compromise solutions; this step, as observed before, should lead to a "satisfactum" after a small number of iterations. This approach thus seems to represent a promising tool for analyzing forest watershed resources management problems subject to imprecision, a situation prevalent in many forest watershed management objectives.

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Appendix 1

Keyboard Controls of PARETO RACE

(SPACE) BAR: "Accelerator"	Proceed in the current direction at constant speed.
F1: "Gears Backward"	Increase speed in a backward direction.
F2: "Gears Forward"	Increase the speed in a forward direction.
F3: Fix	Take the current value of a specified goal as an unconditional bound.
F4: Relax	Release the unconditional bound of the fixed goal set earlier.
F5: "Brakes"	Reduce speed.
num: "Turn"	Change the current direction of motion by pressing the goal's corresponding number key once or several times.
F10: Exit	Return to the main menu.

The use of PARETO RACE is like driving a car on an n-dimensional ($n \leq 10$) road. The driver can use gears, accelerator and brakes, and steer by pressing the keys of an IBM/PC1.

Predicting Individual Log Dimensions and Grade from Hardwood Cruise Data

Daniel A. Yaussy and Robert L. Brisbin[1]

Abstract.--The software described allows the estimation of board-foot volume and numbers of logs by log grade in a hardwood stand based on cruise data. A two-stage estimation procedure was developed using regression techniques and linear discriminant analysis. A bucking simulator is then used to calculate the scaling diameter and length of each log.

STUMP, a System of Timber Utilization and Mill Processing, is being developed as a software package that incorporates hardwood timber quality in the estimation of yield and value from the stump through the mill. This program is an integrated software package that consists of four modules and data entry routines which use standard timber cruise or log scale entries plus the quality measures of tree or log grade (Hanks 1976, Rast et al. 1973) to estimate yield and value by log and lumber grade. There are many programs on the market that process and summarize hardwood cruise data, yet few of these programs incorporate a measure of tree quality as an input. This usually means that an accurate estimate of intermediate or end-product distribution is lacking. This, in turn, limits the effectiveness of the program in providing an adequate estimate of the value of the resource. The development of STUMP is partially funded by a grant from the Forest Resources Systems Institute (FORS)[2] to integrate quality-related research into a package that can be used to evaluate the impact of tree and log quality on the value and volume of intermediate and end products.

The first module of the system is used for woodland inventory and timber appraisal. Output consists of volume and value estimates by species and end product (i.e., lumber grade and veneer). The second module uses the same tree cruise data and estimates the size and grade of logs produced by each tree. The information is summarized by length, scaling diameter, and log grade for each species along with an estimate of stumpage or delivered price. In the third module, log scale information from the second module or from actual log scale data will be used to maintain mill yard inventory by quality classes and to estimate end product yields. The fourth module will monitor production and maintain end product inventory records. Landowners, service foresters, consultants, loggers, and sawmill managers will find STUMP useful for estimating their timber resource.

Module 1 uses existing hardwood tree grade equations to predict expected lumber grade yields from graded trees (Hanks 1976, Hanks and Brisbin 1978). Log grade equations have been developed for predicting lumber grade yields from log characteristics (Howard and Yaussy 1986, Yaussy 1986, Yaussy 1987, Yaussy and Brisbin 1983) and are used in Module 3. Module 2 uses newly developed models to predict merchantable log yields and sizes from tree cruise data. The remainder of this paper focuses on the development of Module 2.

Developing Models for Module 2

The purpose of the second module is to provide information about the size, quality, and value of sawlogs and veneer logs that can be produced from a tract of timber (the procedures in this section are described in detail in Yaussy et al. 1988). An estimation of the number and volume of cut logs that can be produced from a tract of timber along with diameter, length, and grade distributions will be useful to the seller, logger, or purchaser of the tract. Independent loggers can use the information to more accurately define production costs and to estimate stumpage or delivered log values, and mill managers can estimate the quantity and quality of logs that would be added to their mill yard inventory from a timber sale.

New research was needed to describe the relationship between log quality and size and tree quality and size. We determined that the best approach would be to estimate the Interna-

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[2]This project was partially funded by the Forest Resources Systems Institute, which receives Federal financial assistance. Benefits of the Forest Resources Systems Institute are available to all eligible persons regardless of sex, race, color, national origin, religion, handicaps, or age.

tional one-fourth inch gross board-foot volume distribution by log grade and the distribution of bucked logs by log grade. These two quantities are highly correlated. A two-staged estimation procedure was developed to take advantage of this correlation. The first stage estimates the volumes by log grade. The second uses these estimated volumes to help predict the numbers of bucked logs by log grade.

To increase user acceptance of these models, only variables commonly collected in a tree cruise were utilized:

1. Species.
2. Diameter at breast height, in inches (D).
3. Merchantable saw log height (H) defined as the height in 16-foot logs and half logs to the small end of the highest bole section which would produce a grade 3 log.
4. USDA Forest Service hardwood tree grade.

Tree grade may not be a truly common variable in hardwood tree cruises; however, it is the least that is required to achieve any differentiation of quality in log grades.

Since the volumes of the three log grades must sum to the total merchantable sawlog volume, these volumes are not independent of each other. This interdependence indicated that multivariate regression was the appropriate technique to model these relationships. The difference in volume distribution due to the differences in tree grade was accounted for by the use of dummy variables. The full volume estimation model from which the individual species models are derived is large and complex:

$$V_i = b_{i0} + b_{i1}D + b_{i2}D^2 + b_{i3}H + b_{i4}DH + b_{i5}D^2H + b_{i6}G_2 + b_{i7}DG_2 + b_{i8}D^2G_2 + b_{i9}HG_2 + b_{i10}DHG_2 + b_{i11}D^2HG_2 + b_{i12}G_3 + b_{i13}DG_3 + b_{i14}D^2G_3 + b_{i15}HG_3 + b_{i16}DHG_3 + b_{i17}D^2HG_3 \quad [1]$$

where

V_i= gross International one-fourth inch board-foot volume for log grade i, i=1,2,3

G_k= dummy variable indicating tree grade, k=2,3:

Tree grade	G_2	G_3
1	0	0
2	1	0
3	0	1

b_{ij}= coefficients determined by regression, j=0,...,17.

It was originally intended that the same reduced model form would be used for all species with the species differences accounted for with the different sets of coefficients; however this method did not produce models with adequate precision. Therefore, the full model [1] was reduced by a process of backward elimination for each species. This involved the elimination of the least significant variable, then rerunning the reduced model. This process was repeated until all remaining variables were statistically significant at an .05 implied level of significance. This produced a different model for each of the 11 species modeled (table 1).

Table 1.--Species substitution used in application of models in Module 2.

Species for which models have been developed	Species groups for which Module 2 assigns substitutes
Basswood (BAS)	Cucumber
	Magnolia
Black cherry (BLC)	Ash
	Black walnut
Black oak (BLO)	Misc. red oaks
	Southern red oak
	Scarlet oak
Chestnut oak (CHO)	
Northern red oak (NRO)	Cherrybark oak
Paper birch (PAB)	
Red maple (REM)	Misc. soft hardwoods
	Silver maple
	Hickory
	Pecan
	River birch
Sugar maple (SUM)	Misc. hard hardwoods
	Beech
White oak (WHO)	Misc. white oaks
Yellow birch (YEB)	Sweet birch
	Elm
	Cottonwood
Yellow-poplar (YEP)	Aspen

Trying to estimate the distribution of bucked logs by log grade presented the problem of predicting a discrete variable. Linear discriminant analysis develops equations which can be used to estimate the probability that an observation fits into a certain category. In this instance, the categories were the numbers of logs of each log grade that a tree will produce (i.e., 0, 1, 2, 3, 4). This meant that there might be an equation for each possible category in each of three log grades, in each of 11 species, 198 equations. With this in mind, it was decided to limit the number of variables in each equation to five. The linear discriminant function used for each species was:

$$f_{in} = a_{in0} + a_{in1}G_2 + a_{in2}G_3 + a_{in3}V_1/D^2 + a_{in4}V_2/D^2 + a_{in5}V_3/D^2 \quad [2]$$

where

f_{in} = linear discriminant function value for log grade i and number of logs n, n=0,...,4

a_{inm} = coefficients determined by discriminant analysis, m=0,...,5

The model form [2] was the same for each species, but each has its own set of coefficients.

One-quarter of the data available were set aside to be used as a validation data set. The multivariate equations [1] were applied to the trees in the validation data set. The results (fig. 1a)

indicate that total merchantable volume by species is predicted within 5% of the actual. All log grade volumes are within 20% except for log grade 3 chestnut and northern red oaks. These cells had relatively low numbers of logs in both the development and validation sets compared to the rest of the volumes for other grades of those species.

Actual log grade volumes of the validation trees were used as input to the discriminant functions [2] for testing. The total predicted numbers of logs is within 10% for all species except one, and is very acceptable for each log grade within species, except for grade 3 northern red oak (fig. 1b). It is interesting that the multivariate equations [1] overestimated the grade 3 volume for this species by such a wide margin, yet the discriminant functions [2] underestimated the number of logs by the same percentage. This might be due to the low number of grade 3 northern red oak logs in the study.

For the predicted values that deviated from the actual, the deviations are usually negative. This is due to the nature of the system being modeled. The probability of a tree producing no logs or one log of a certain grade is much higher than the probability of producing two, three, or four logs of that grade. And this model, like most models, tends toward the mean and avoids the extremes. This yields a slight negative bias even when the model is used with the development data set.

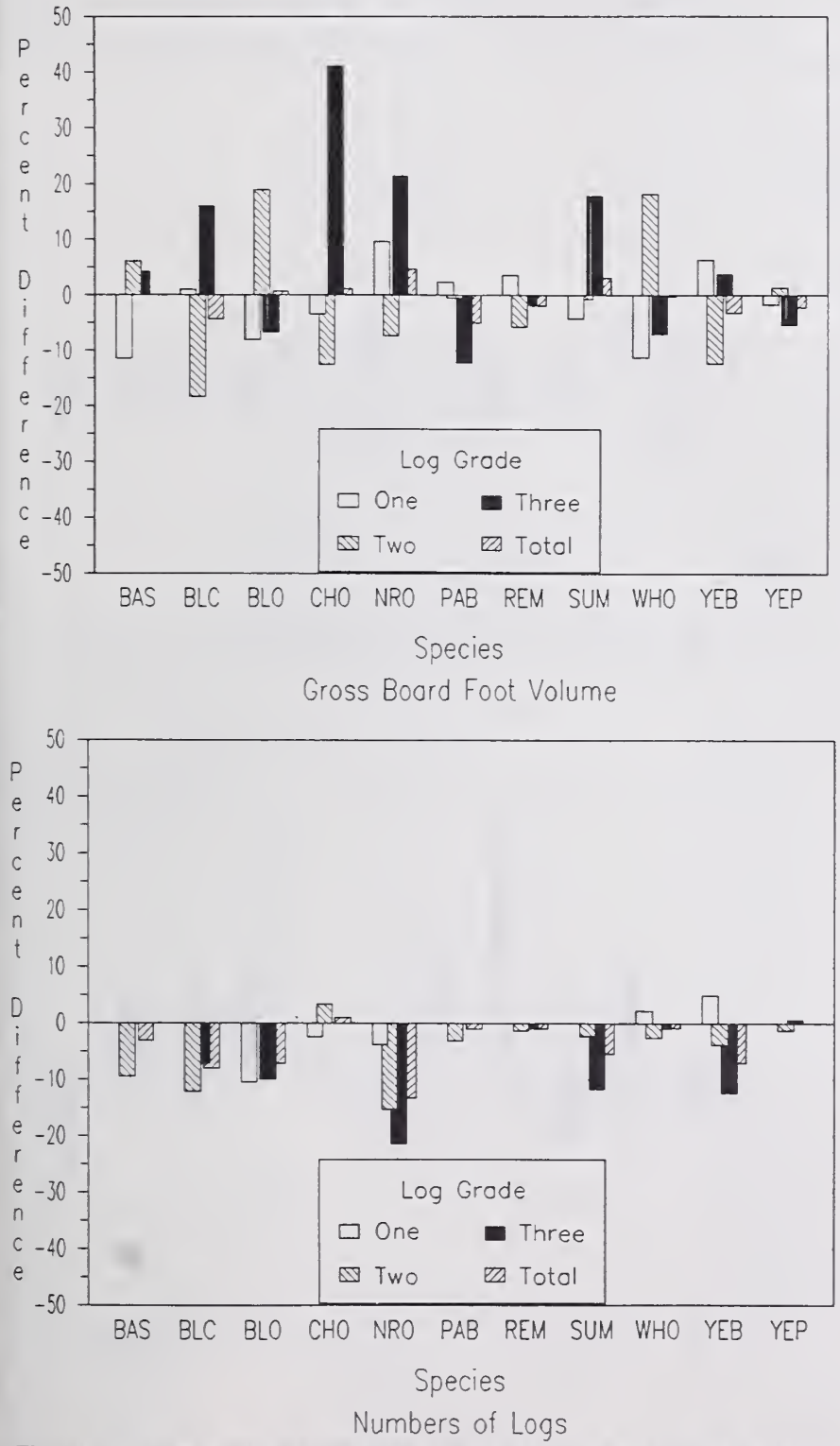


Figure 1.-- Differences between actual values of validation data set and those predicted by the models developed for Module 2 of STUMP: (a) gross board-foot volume; (b) numbers of logs.

Applying the Models

The models were developed for only 11 species. Module 2 has a species substitution list that allows for the input of 32 separate species groups (table 1). For some trees, the use of the two models will produce seemingly contradictory results (e.g., log grades with volumes but no estimated logs). This inconsistency occurs because regression equations almost always result in a nonzero volume estimation for each grade. A model form like that presented by Reed et al. (1987) would not produce these results.

The estimated volume can be one of three classes:

1. Large enough to produce a positive number of logs when fit into the discriminant functions.
2. Too small to produce a positive number of logs.
3. A small negative volume resulting in zero logs for that log grade.

Figure 1a indicated that the volume equations are fairly unbiased across species. If the small volumes were dropped, the overall estimate for the cruise would be negatively biased. Therefore, the program adds the unused volumes associated with zero logs to the next tree of the same species. This also provides for the occasional grade 1 log produced from a grade 3 tree.

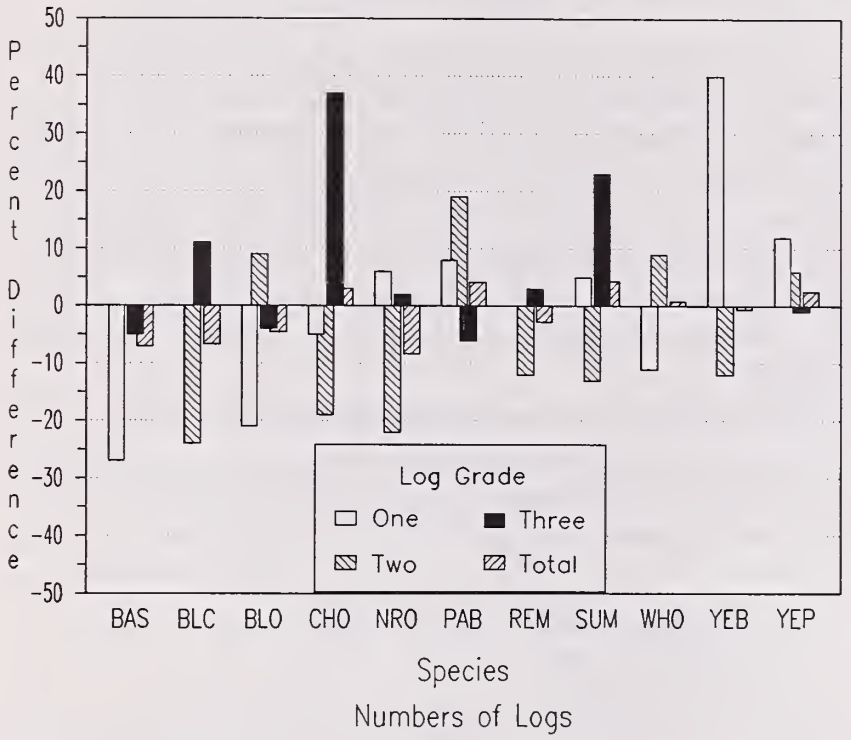
The next step in the program is to take the estimated numbers of logs and adjusted volumes and "buck" the tree. The Forest Service log grades provide specific guidelines as to minimum log lengths and scaling diameters for each log grade. With this information, dbh, volume, number of logs, and an estimate of taper, the log dimensions can be estimated. Specific taper equations developed for the majority of the species require that total height be measured for each tree. This is not a realistic option on a timber cruise. A general "rule of thumb" taper was incorporated into the program. The International scaling taper of 2 inches per 16 feet was assumed, but this was not enough. Carl Mize[3] has suggested that 2 1/2 inches taper per 16 feet is more realistic for hardwoods. It works well in this case after it

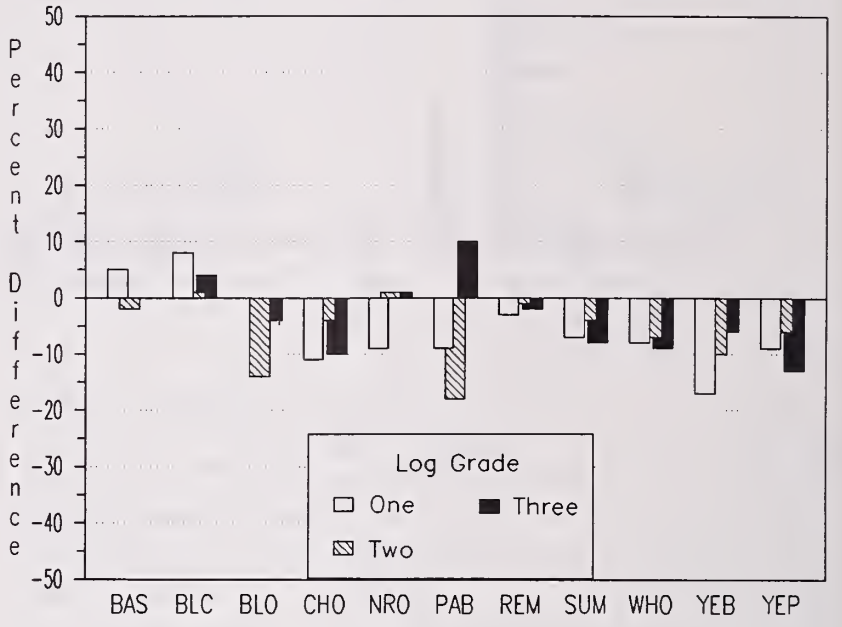
[3]Cited in "What to cut: logs or pulp?", Forest Industries magazine, June 1987, p. ES5.

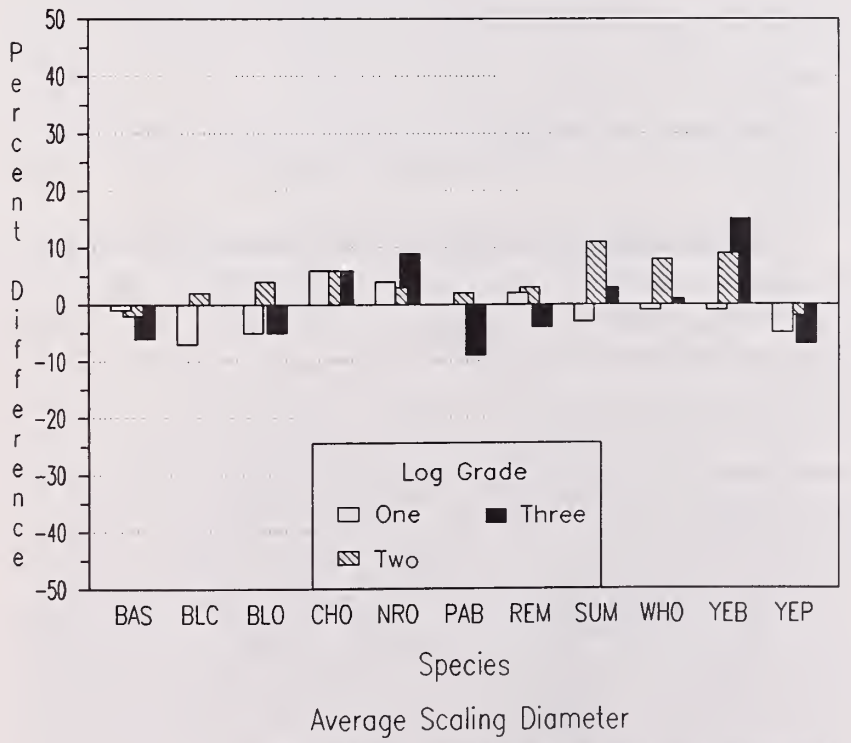
was adjusted to fit the average Girard Form Class from the data for each species and tree grade. Another assumption made for the program is that the highest grade material occurs in the butt portion of the tree.

The program provides for the input of a veneer bolt length for each tree. When a veneer bolt is present, the small-end diameter and International volume are calculated. Then if the veneer length is less than 16 feet, one of the estimated logs of the highest grade present is deleted and the volumes adjusted accordingly. If the veneer length exceeds 16 feet, two logs are deleted. Small-end diameters and log lengths are calculated for the remaining logs in each log grade. Volumes are then recalculated for each log by fitting the estimated diameters and log lengths into either the Doyle or International scaling rule. If an estimation of cull was input for the tree, it is assigned to each log and bolt produced by that tree and a net volume figure is calculated.

The data set used to validate the models was again used to validate the program calculations. The difference between the actual volumes, numbers of logs, average scaling diameter, and average log lengths and the results of the Module 2 calculations are presented in figures 2a-2d as percentages by log grade for each species. Total volume across log grades is within 10% for each species except for yellow poplar (14%). Individual log grade volumes by species are within 25% for all but grade 3 chestnut oak. The same bounds hold for the predicted numbers of logs except for the addition of grade 1 yellow birch. The graphs for average scaling diameter and log length are much less variable than the previous two graphs. Almost all average diameters are within 10%, while all but two average log lengths







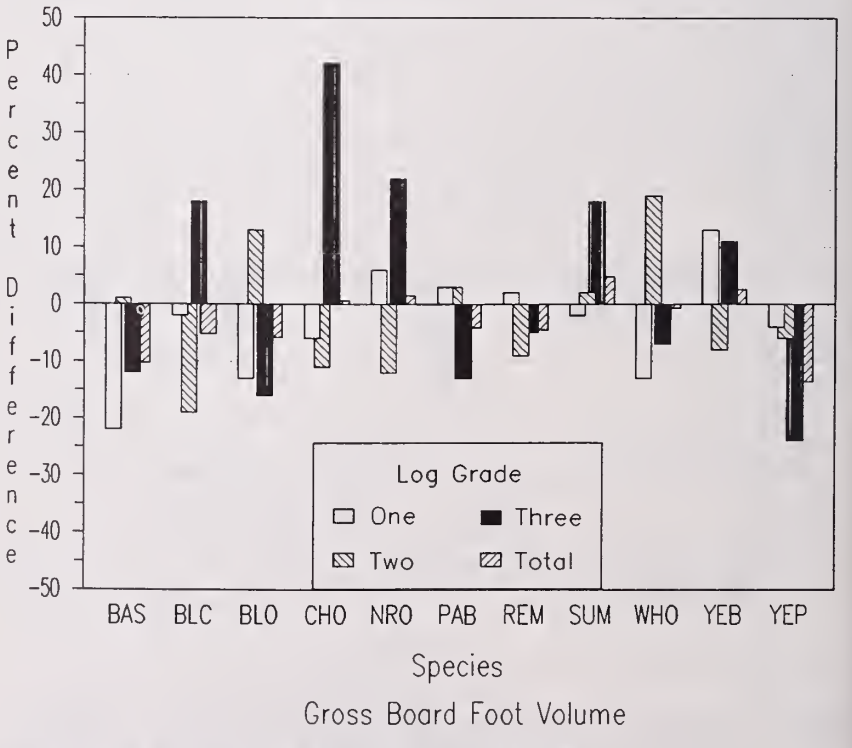


Figure 2.-- Differences between actual values of validation data set and corresponding results from Module 2 of STUMP: (a) numbers of logs; (b) average scaling diameter; (c) average log length; (d) gross board-foot volume.

Table 2.--Sample output from Module 2 of STUMP.

Veneer/Bolts	Total	Per acre	Std. Err.	Confidence interval	
Number of logs	6	2	093	1	2
Gross int. bf vol.	1117	279	16.382	247	311
Net int. bf vol.	1092	273	16.016	241	304
Delivered Price($)	997	249	15.184	219	279
Grade 1 logs	**Total**	**Per acre**	**Std. err.**	**Confidence interval**	
Number of logs	78	20	.530	18	21
Gross int. bf vol.	12489	3122	74.977	2975	3270
Net int. bf vol.	12427	3107	74.541	2960	3253
Delivered Price($)	2538	634	18.007	599	670
Grade 2 logs	**Total**	**Per acre**	**Std. err.**	**Confidence interval**	
Number of logs	221	55	1.384	53	58
Gross int. bf vol.	22027	5507	125.043	5261	5752
Net int. bf vol.	21672	5418	122.945	5176	5660
Delivered Price($)	2571	643	14.629	614	672
Grade 3 logs	**Total**	**Per acre**	**Std. err.**	**Confidence interval**	
Number of logs	296	74	2.081	70	78
Gross int. bf vol.	17112	4278	107.237	4067	4489
Net int. bf vol.	16805	4201	105.160	3995	4408
Delivered Price($)	1425	356	8.860	339	374

		Veneer					Grade 1				Grade 2					Grade 3				
LENGTH		≤8	10	12	14	16≥	10	12	14	16	8	10	12	14	16	8	10	12	14	16
	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	35	0	0	0
	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	23	4	18
	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27	18	0	9	11
	11	0	0	0	0	0	0	0	0	0	5	16	16	0	18	0	18	0	4	9
S	12	0	0	0	0	0	6	0	0	0	20	7	4	3	8	10	0	9	12	4
C	13	0	0	0	0	0	15	7	0	0	6	2	8	3	7	3	6	2	0	4
A	14	0	0	3	0	0	4	0	3	6	3	12	0	3	8	5	2	0	0	2
L	15	0	0	0	0	0	0	0	0	3	3	4	3	4	3	2	4	5	0	2
I	16	0	0	0	0	0	0	2	0	0	0	5	0	2	4	2	0	2	0	0
N	17	0	0	0	0	0	0	2	2	2	2	0	0	3	6	2	1	0	0	0
G	18	0	0	0	0	0	0	2	0	2	2	0	0	2	0	9	0	1	1	0
	19	0	0	0	0	0	1	0	0	6	5	2	2	1	0	2	2	2	0	0
D	20	0	0	0	0	0	1	0	0	2	5	4	0	0	1	1	0	0	0	0
I	21	0	0	0	0	1	0	2	0	0	3	0	0	0	0	0	0	0	0	0
A	22	0	0	0	0	0	1	2	0	0	1	0	0	2	0	1	1	0	0	0
M	23	0	0	0	0	0	0	0	2	0	1	0	0	0	0	1	0	0	0	0
E	24	0	1	0	0	0	0	0	0	3	1	0	0	0	1	0	0	0	0	0
T	25	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
E	26	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
R	27	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	32+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

are within 15%. There is, however, a noticeable negative bias in the log lengths, though it does not seem to carry through to the volume estimates.

Program Output

Module 2 is designed to accept four types of sampling schemes: (1) 100% inventory, (2) point-sampling cruise, (3) fixed-plot cruise, and (4) strip cruise. The number and volume of the logs are adjusted accordingly. The major output of Module 2 is a summary by species groups of volume, value, and a diameter/length distribution by log grade (table 2). This can be routed to the printer, a disk file, or both. A user-modified file contains prices, in dollars per thousand, for each log grade and veneer class for each species group. These prices, Doyle or International, can be stumpage, delivered log, or any other price the operator wants to use.

A log file is an optional output which contains a listing of the species, scaling diameter, log length, cull proportion, and log grade of each estimated log produced from the stand. This file can be used for further analysis and it is in the format of input for Module 3. No graphics are provided by Module 2; however, an optional graphics file containing summaries of volume, value, and numbers of logs is available for use with other packages.

Program Availability

STUMP is designed to work on MS-DOS machines with at least 256K RAM, two floppy disk drives, or one floppy and one hard disk. The entire STUMP software package should be completed by the fall of 1988. The user's guide should be completed by January 1989. FORS will handle distribution and support of the package.

Future Applications

There are tentative plans to incorporate parts of STUMP into individual tree hardwood growth and yield simulators such as OAKSIM (Hilt 1985), and possibly into some form of harvest simulator. This would provide these packages with improved economic estimates to aid in the development of management guidelines.

Since STUMP is mostly written in FORTRAN, it is our intention to produce a Data General version to be used by the National Forest Systems of the Forest Service.

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Designing An Optimal Wood Utilization System Using a De Novo Programming Approach

Guillermo A. Mendoza and B. Bruce Bare[1]

Abstract.--Describes a de novo programming approach to production planning in the forest products industry. Unlike traditional models which optimize suboptimal systems with a given set of resources, the de novo approach focuses on designing optimal systems where resource constraints are designed optimally.

Efficient utilization of raw materials has been a long-time concern of the forest products industry. Here, efficiency is measured not only in terms of increased product yield per unit input, but also in economic terms. Several techniques have been developed to achieve economic efficiency in wood products utilization. Most notable among these are the use of mathematical models like linear programming (Carino 1986, Mendoza and Bare 1986), dynamic programming (Faaland and Briggs 1984, Pnevmaticos 1972), simulation (Galbraith and Meng 1981, Treiber and Boyle 1980, Wagner and Taylor 1983), and queuing theory (Carino and Taylor 1982, Maurer 1968). Successful application of some of these techniques also has been reported (Eng et al. 1986, Hay and Dahl 1984, Lembersky and Chi 1984, Bare et al. 1984).

One of the major limitations of these models is that they are designed primarily to determine optimal solutions to prespecified problems. In general, these models optimize systems with given sets of fixed resources. However, in real world planning problems, resources often are not fixed, but can be changed depending upon their economic value, marketability, or overall contribution to the production system. Hence, the production planning problem should not viewed as simply a problem of determining an optimal output schedule for an assumed fixed level of production inputs. Instead, the scope of planning must be enlarged to encompass the design of an optimal system where the production inputs are not specified *a priori* as fixed, but must be optimally designed. The question should be, "What kind, and how much, of each resource should be acquired so that the resulting production system yields the best returns?"

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The forest products industry is a natural environment for testing this approach to production planning. Wood utilization planning--from the primary processing of raw materials to the manufacture of final products--is a production-intensive system where a variety of inputs are used at various stages of production. Given such highly productive systems, an underutilization of raw materials, or an inefficient allocation of production inputs may result in substantial increases in production costs and less profit. Thus, it is important that all resources be efficiently allocated during the planning process.

This paper examines the use of de novo programming in a wood utilization context, and illustrates the design capabilities of the model with a sample problem. De novo programming is used because it offers the capability of designing optimal production systems within given budgetary limitations.

De Novo Programming

This section summarizes the de novo approach, particularly its methodology as it relates to linear programming (LP). This approach recognizes that not all constraints are "hard" (i.e., fixed) and, hence, not subject to change. Instead, some constraints are assumed to be "soft;" to be determined through analysis. Thus, using de novo programming, the optimal production schedule is simultaneously determined with the right hand sides of the soft constraints.

Zeleny's (1986b) External Reconstruction Algorithm (ERA) is an example of a de novo algorithm which can solve a range of problems. The algorithm takes advantage of the fact that only binding constraints characterize optimal solutions to LP problems. Thus, initially, there is no need to work with all constraints. Instead, the ERA is used to reconstruct all fixed, and

potentially binding constraints while determining the optimal levels of the soft constraints.

The ERA is an iterative algorithm which works through the use of an aggregate constraint which (initially) consists of: (1) all fixed inequality constraints to be reconstructed during subsequent iterations, (2) all soft inequality constraints to be designed, or (3) a combination of the above. All equality constraints are taken as fixed and are excluded from the aggregate constraint.

At each iteration of the ERA, the most violated fixed inequality is decoupled from the aggregate constraint and a new LP is solved. The new problem consists of one additional fixed constraint (the one decoupled) and the revised aggregate constraint. This process of decoupling and resolving is continued until all of the fixed inequalities are satisfied. Then the optimal levels for the soft constraints being designed are also available.

A full description of the ERA is available in Zeleny (1986a, 1986b) and an application of this approach to land management planning is described by Bare and Mendoza (1988).

Sample Problem

To demonstrate the use of de novo programming in designing an optimal wood utilization system, a sample problem adapted from Pearse and Sydneysmith (1966) is used. This sample problem was selected because it is simple enough for illustrative purposes and yet it is representative of the nature of production planning problems present in the forest products industry. Some aspects of the sample problem such as (1) the conversion or recovery rates for different primary and secondary processing, (2) the production costs, and (3) the prices of finished products are notably dated. However, for the purpose of this paper, which is primarily to illustrate the methodology of de novo programming, it was deemed unnecessary to update these coefficients.

The problem described by Pearse and Sydneysmith (1966) involves the allocation of a fixed quantity of coniferous logs to several interdependent conversion facilities, where the objective of the allocation is to maximize the net value of the resources. The problem involves the allocation of 12 primary inputs (i.e., species and grade-dependent log types) to 35 intermediate and 59 final activities. The intermediate activities consists of log sawing (producing lumber, chips and hog fuel), log peeling (producing veneer, chips and hog fuel) and log chipping (producing chips). The final activities consists of plywood, pulp, lumber, and hog fuel.

In their formulation, no physical limitations are imposed on the productive capacities of the conversion facilities. Thus, a long term view of production planning is adopted. Further, the problem is structured and solved as a regional solution and is not specific to an individual firm. As shown below, this long-term view fits the framework of de novo programming very closely as the latter is most useful when resource capacities are viewed as variable and subject to design.

For a more detailed description of the sample problem, readers are referred to Pearse and Sydneysmith's (1966) paper. To highlight the design capabilities of de novo programming various cases--each revolving around the Pearse and Sydneysmith model--are presented.

Case I. Optimizing a Given System

This case illustrates the traditional concept of optimization using LP where all constraints are collectively treated as fixed or given. The problem described in Pearse and Sydneysmith (1966) is slightly modified for this and subsequent cases by imposing some demand and market restrictions for lumber products. Demand restrictions are specified as minimum levels of production required in order to meet the obligations of the region to its consumers. A minimum level of 2 million cubic feet is specified for all lumber products. Likewise, market restrictions are specified to limit the maximum amount of product that the market can absorb. This is specified as 50 million cubic feet for all lumber products. With these modifications, the problem solved is identical to that described in the original paper.

To simplify the presentation of results, only the right-hand-sides (i.e., resource use) and objective function values associated with the various solutions are presented. However, this information is adequate for describing the advantages of "designing an optimal system" rather than optimizing a given system.

Table 1 shows the "given" amount of resources (i.e., log availability) and their corresponding usage. The results in Case I suggest that all log types have been utilized, and that the maximum profit is $319.04 million[2]. Given this information, one may wonder if it pays to buy additional logs, assuming that a log market is available.[3] Exploring this possibility of log purchase further, the next question is how much of each log type should be bought? This question then brings out the idea of "designing the optimal amount " of resource inputs--in this case the optimal amount of each log type. The design problem therefore is not how to optimize the returns from a "given" production system with fixed resource inputs, but rather how to determine the optimal level of resource inputs. Hence, the right-hand-side (RHS) value is no longer fixed but is considered "soft."

Case II. Designing an Optimal System

The problem used in this case is the same problem used in Case I. However, instead of assuming a fixed distribution of log

[2]*The optimal profit from Pearse and Sydneysmith (1966) was $325.5 million. The difference is due to the added demand and market restrictions for lumber.*

[3]*The shadow prices of the log availability constraints provide this information. However, they assume that each RHS is changed sequentially. De novo programming permits all RHS's to be altered simultaneously.*

Table 1.--Log availability and allocation for Case I (million ft³).

Log grade and species		Log type	Log availability	Log allocation
D. fir	#l plr	1	6.1	6.1
	#2 plr	2	14.2	14.2
	#3 plr	3	28.4	28.4
	#4 plr	4	18.3	18.3
	#2 swlg.	5	46.7	46.7
	#3 swlg.	6	89.5	89.5
Hemlock	#l swlg.	7	13.8	13.8
	#2 swlg.	8	50.0	50.0
	#3 swlg.	9	213.6	213.6
Spruce	#l swlg	10	1.3	1.3
	#2 swlg.	11	11.4	11.4
	#3 swlg.	12	19.8	119.8
	Total		513.1	513.1

Optimal profit = $319.04 million.

inputs as described in table 1, it is assumed that the log input availability is flexible and can be designed (i.e., the optimal volume by log-type is to be determined).

The "hard" constraints consist of those that must be satisfied. In this case, all the material balance equations describing the input-output flow of intermediate to final products are considered hard.

The "soft" constraints consist of those related to log inputs. Before presenting the aggregate constraint, it should be pointed out that the problem addressed in Case II is modified from Case I. That is, the question now is "what should be the optimal level of each log type?" It is therefore assumed initially that any additional log type can be obtained either by purchasing them from a regional log market or from another region.

The other question that is addressed is "what are the limits to the design problem," or "what are the criteria for designing the system?" One logical criterion is budget. That is, the cost of each log type is specified and logs are purchased subject to this limitation. For this problem, the cost schedule used is described in table 2.

The aggregate constraint can now be described as:

$$\sum_{j=1}^{n} \left(\sum_{i=1}^{\Omega} a_{ij} X_j \right) \leq 13.455 \text{ (\$ million)}$$

where Ω is the set of "soft" constraints.

The aggregate constraint simply states that a limited budget of $13.455 million is available for log purchase. Using this dollar amount allows comparison of the solutions obtained in Cases I and II. Note that the difference between Cases I and II is the addition of the aggregate constraint in lieu of the "fixed" log input levels described in Case I. All the other "hard" constraints are the same for both cases. The solution for Case II is summarized in table 3.

Table 2.--Cost schedule for various log types.

Log type	Cost[1] *(100 ft³)*	Log availability *(million ft³)*	Total purchase Cost *($ million)*
1	54	6.1	3.294
2	49.5	14.2	7.029
3	45	28.4	12.780
4	35	18.3	6.405
5	27	46.7	12.609
6	24.75	89.5	22.151
7	22.5	13.8	3.105
8	20.25	50.0	l0.125
9	23.25	213.6	49.662
10	27	1.3	.351
11	22.5	1.4	2.565
12	23.25	19.8	4.4737
	Total purchase cost		13.455

[1]*Costs were estimated at about 75% of log selling prices described in Pearse and Sydneysmith (1966).*

Table 3.--Optimally designed resource inputs.

Log type	Optimal RHS design *(million ft³)*
1	0
2	0
3	0
4	0
5	330.14
6	0
7	0
8	22.22
9	0
10	151.51
11	0
12	0
Total	503.87
Optimal profit =	$485.23 million.
Total purchase cost =	$13.5 million.

The solution from table 3 shows the optimal design of the system includes; 330.14 million cubic feet of log type 5; 22.22 million cubic feet of log type 8, and 151.51 million cubic feet of log type l0. Comparing the two solutions shown in tables 1 and 3 reveals that 9.23 million cubic feet less are required to produce a total increase in net returns of $166.2 million. And, both solutions satisfy the budget constraint. This presents an interesting situation. However, one might ask if the recommended amount of log types 5 and 10 can be obtained from the log market at the assumed constant costs shown in table 2.

To extend Case II, further analysis was made by placing a restriction on the maximum amount for log types 5 and l0 of l00 and 200 million cubic feet, respectively. Given this restriction, the optimal RHS design is given in table 4. Now, log type 8 drops out of solution and is replaced by log types 1 and 7.

Table 4.--Optimal design given restrictions on log market.

Log type	Optimal RHS design *(million ft³)*
1	19.03
2	0
3	0
4	0
5	l00
6	0
7	192.3
8	0
9	0
10	200
11	0
12	0
Optimal profit =	$385.78 million.
Total purchase cost =	$13.5 million.

Case III. Multi-Criteria Optimal Design

Moving from the single criterion situation in Cases I and II, Case III illustrates the problem of designing an optimal system when two or more objectives exist. Case II illustrated how to design an optimal system with only one objective. Now, to demonstrate a multicriteria optimal design situation, the sample problem is slightly modified to include a second objective. This objective involves the minimization of total processing costs for lumber, veneer, and chips.

In multi-objective programming (MOP) the concept of "ideal solution" is often utilized. This is a solution where all objectives are simultaneously optimized. In traditional MOP (i.e., where the constraints are collectively treated as fixed), the "ideal solution" is, in general, infeasible. However, if some of the constraints can be considered "soft" or "flexible" (i.e., under a de novo formulation), it is conceivable that the "ideal solution" may be made feasible through reallocation or design of the soft RHS. This problem is examined in Case III.

The results from the analysis indicate that the "ideal solution" shown in table 5 is indeed infeasible when the RHS are not designed. Thus the maximum profit can not be achieved while simultaneously minimizing costs. Furthermore, even using a de novo formulation (i.e., where the RHS of the log inputs are designed), the "ideal solution" is still infeasible. This suggests that the ideal values of the two objectives cannot be attained merely by designing the "soft" constraints. The other set of constraints (i.e., the "hard" material balance equations, the demand and market restrictions, and the additional constraints requiring the values of the objectives to be at their ideal values), are collectively, causing the infeasibility of the "ideal solution."

Table 5.--Comparison of solutions ($million).

Objective	Ideal solution[a]	Solution 1[b]	Solution 2[b]	Solution 3[c]
Profit	319.04	319.04	268.97	248.13
Processing cost	12.50	18.63	12.50	12.50

[a] *Infeasible.*

[b] *Obtained under a de novo formulation.*

[c] *Obtained without designing the RHS's.*

Under these circumstances, de novo programming still can be used to examine how to best design the RHS while simultaneously attaining the best possible value (less than the "ideal value") of one of the objectives. This can be accomplished by including the aggregate constraint for the log inputs plus another constraint restricting one of the objectives to its ideal value. For instance, one can minimize processing cost while setting profit at its ideal value. This formulation yields the results described as solution 1 in table 5.

Solution 1 was obtained by minimizing processing costs while setting a constraint on profits to be $319.4 million. The designed RHS under this scenario are shown in table 6. Clearly, additional dollars of budget are required in order to meet the profit constraint, even with the design of the RHS. For comparison, another de novo problem was formulated and solved. Shown as solution 2, in table 5, this problem consists of maximizing profits subject to a processing cost constraint of no more than $12.5 million. Again, even with a de novo formulation, the ideal solution is unattainable. Solution 3 in table 5 illustrates the "cost" of not designing optimal RHS's. This solution is attained by maximizing profit subject to a processing cost constraint of $12.5 million without designing the RHS's of the log availability constraints. Not only is the ideal solution infeasible, but the maximum profit, in comparison to solution 2, is reduced.

Table 6.--Optimal RHS design based on minimization of processing cost objective.

Log type	Optimal RHS design *(million ft³)*
1	23.43
2	1.43
3	8.57
4	0
5	l07.89
6	0
7	6.25
8	0
9	12.5
10	310.7
11	0
12	0
Objective	**Value**
Profit	$319.04 million
Processing cost	$18.63 million

Case IV. Designing for the System Ideal

Case II described how to optimally design the RHS, given a single objective. Case III, on the other hand, examined a multicriteria design problem where two objectives are considered. The ideal solution described in Case III consists of the optimal solution of each objective when optimized separately with a given fixed level of log inputs. In light of the results in Case II, one can think of another solution consisting of the optimal values of the objective functions which are based on optimally-designed RHS. For instance, as previously shown, the optimally-designed value for the profit objective function is $485.23 million, while the optimal solution given fixed RHS values is $319.04 million. The solution consisting of the optimally-designed objective function values is referred to as the "system ideal" (Zeleny 1986a). This solution is better than the ideal solution described in Case II.

Another interesting planning problem is to examine if merely designing the RHS's can make the system ideal feasible or, if not, how much would it cost to attain the system ideal. Again, this is in contrast to the traditional concept of planning which is limited to examining alternative solutions given fixed production inputs.

To determine the system ideal, it is necessary to find the optimal RHS design based on the processing cost objective. This analysis yields an optimal cost objective equal to $12.15 million. Hence, the system ideal consists of the following values shown below.

Objective	Ideal solution	System ideal
Profit ($ million)	319.04	485.23
Processing cost ($ million)	12.50	12.15

The system ideal is also infeasible even with the designing of the RHS's. Again, this may be due to the other constraints that are treated as fixed (i.e., not to be designed) such as the demand and market restrictions imposed on the lumber products. At this point, the advantages of de novo programming over traditional models like linear programming may be further described by also designing these demand and market restrictions instead of assuming them to be fixed.

Summary

This paper has briefly introduced the subject of soft optimization using a de novo formulation of single and multiple objective LP. Following the discussion, a sample log allocation problem was analyzed using four case examples: (1) Case I: optimizing the single objective problem as given with all constraints considered hard, (2) Case II: optimizing the single objective problem as given while designing the log availability constraints subject to an aggregate budget limitation, (3) Case III: establishing the "ideal solution" where two of the objective functions are sequentially optimized with all constraints considered hard, (4) Case III: determining if the ideal solution can be made feasible by designing the RHS's of the log availability constraints, and (5) Case IV: obtaining the "system ideal" solution and determining if it can be made feasible by designing the RHS's of the log availability constraints. In both Cases III and IV, it was not possible to attain feasibility by designing the soft constraints. Thus some of the constraints considered hard must be redefined as soft if feasibility is to be achieved. However, the advantage of de novo formulation is illustrated in table 5.

The case studies illustrates the potential savings to be gained by designing optimal production levels and not simply optimizing systems as given. Clearly, to realize the benefits of such models, decisionmakers and analysts must have the flexibility to alter the RHS's of the constraints. While this is not always possible to achieve in the short run, it should be a goal to work towards in the long run.

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Multiple-Expert Knowledge Elicitation for an Intelligent Tutoring System

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Abstract.--Reliable extraction of human knowledge is essential for building expert systems. This may require the input of several experts. A methodology based on the Delphi technique of decision analysis is utilized for collecting and combining expertise from several different individuals. Results of this approach indicate that multiple expertise can be extracted and integrated to improve on knowledge provided by a single expert.

Development of an Intelligent Tutoring System (ITS) for wildfire prevention program planning forms a basis for the investigation of knowledge elicitation methods using several experts. A systematic approach to prevention planning has recently been developed on the San Bernardino National Forest in southern California; however, there is currently no comprehensive document for transferring the methods and rationale of the planning process to other prevention personnel. An intelligent tutor expert system is being constructed which will (1) provide instruction for learning the process and (2) assist the user in creating specific prevention programs.

Increasing urban development adjacent to wildland areas brings people activities and values at risk into closer proximity to areas of high wildfire hazard. This development introduces urban life-styles into wildlands and creates a significantly higher probability for ignitions than occurred with infrequent leisure-time use (Rice 1987). Natural resources are no longer the only values at risk; property damage and personal losses from wildfire may result from urbanization of the interface. Increased use of wildland areas (and the concomitant increase in risk) must be taken into account by those responsible for aligning wildfire prevention programs to specific wildland environments (Bradshaw and Johnson 1988). Fuels management tactics must be designed according to the wildfire threat and values at risk (Franklin 1987). Suppression activities need to accommodate the increased demand for protection and services which, because of human proximity to danger, cannot be denied (Tokle 1987). These demographic trends have created special interest groups related by similar characteristics, interests, and concerns (Rice 1987). Fire prevention programs, fuels management efforts, and fire suppression strategies must be adapted to the changing and unique fire management needs at the interface.

Wildfire prevention programs in the Forest Service, including those dealing with interface fire protection, are subject to efficiency criteria; program costs and resource losses must be minimized. Simple frequencies of ignitions are no longer the primary concern; ignitions which have the greatest potential to become large and/or damaging fires become targeted for prevention budget investment (Bradshaw and Johnson 1988). Wildfire prevention research has recently developed a comprehensive, systematic approach to prevention planning based on the efficiency criteria just mentioned.

The study reported here examines the first of several steps in developing an Intelligent Tutoring System for wildfire prevention planning. Detailed description and understanding of the prevention planning process resides only in the experiences of several prevention personnel. Therefore, it became necessary to extract this knowledge for incorporation into the ITS. Because several individuals were involved in the initial specification and composition of the planning process, inclusion of all these participants seemed desirable. Additionally, certain experts had experienced greater involvement with particular aspects of the process. Their thorough understanding, as well as the personal conceptualization possessed by each expert, was considered essential to a comprehensive representation of prevention planning.

To our knowledge, little has been proposed or accomplished in multiple-expert knowledge acquisition. Mittal and Dym (1985) and Schmoldt (1987) utilized multiple experts for initial knowledge acquisition stages. Prospective sub-problems and solution methods were intimated by protocol analysis from many experts in both reports. The former's results indicated that multiple experts are useful for identifying consistent knowledge, community knowledge, and discrete specialization. They also suggested, in the case of discrete specialization, using

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different experts within the solution of the larger problem; an approach applied by Schmoldt (1987). In addition to the above uses of multiple experts, we feel that it is important to extract in-depth, problem-solving knowledge as it resides in several individuals (community knowledge) and integrate this knowledge into a consistent representation. We are unaware of any such attempts previously.

Prior to presenting our approach to multiple-expert knowledge elicitation, prevention planning is discussed. Because the planning process defined an *a priori* framework for our tutor implementation, significant emphasis is placed on its description in the following section. We also include a brief introduction to intelligent tutoring systems.

PREVENTION PLANNING

To determine whether money spent on prevention reduces wildfire losses, prevention outputs must be balanced against goals established through systematic analysis of fire problems across entire management areas. A prevention planning process developed on the San Bernardino National Forest incorporates a detailed inventory of fire-problematic conditions. Prevention program prescriptions (locally developed and implemented) address these specific conditions; subsequent program evaluation compares fire occurrence and prescription implementation. This detailed approach provides for both accountability in program selection and follow-up assessment of success/failure.

The planning process, though systematic, still contains a large subjective aspect. Several district plans have been developed through the use of this process, but no comprehensive manual details the necessary steps and inherent rationale. To a large extent, application of the process remains a paper and pencil exercise for making and recording subjective analyses and judgments. Consequently, new users experience difficulty in beginning a fire problem analysis (the first, and essential, component of the process). The initially flat learning curve associated with this process makes it difficult for people to get the process started. The current research effort proposes that a knowledge-based tutor could facilitate learning about the planning process, and provide guidance for developing specific prevention programs.

Process Components

The planning process described here consists of the sequence of steps depicted in figure 1. Systematic analysis of fire problems constitutes the primary advantage of this planning approach. Subsequent steps rely on inventories and maps produced in the analysis phase.

Analysis of wildfire ignition problems involves the examination of three independent aspects of the wildfire situation. *Risk* analysis consists of inventorying, ranking, and mapping people activities that have the potential to cause ignitions.

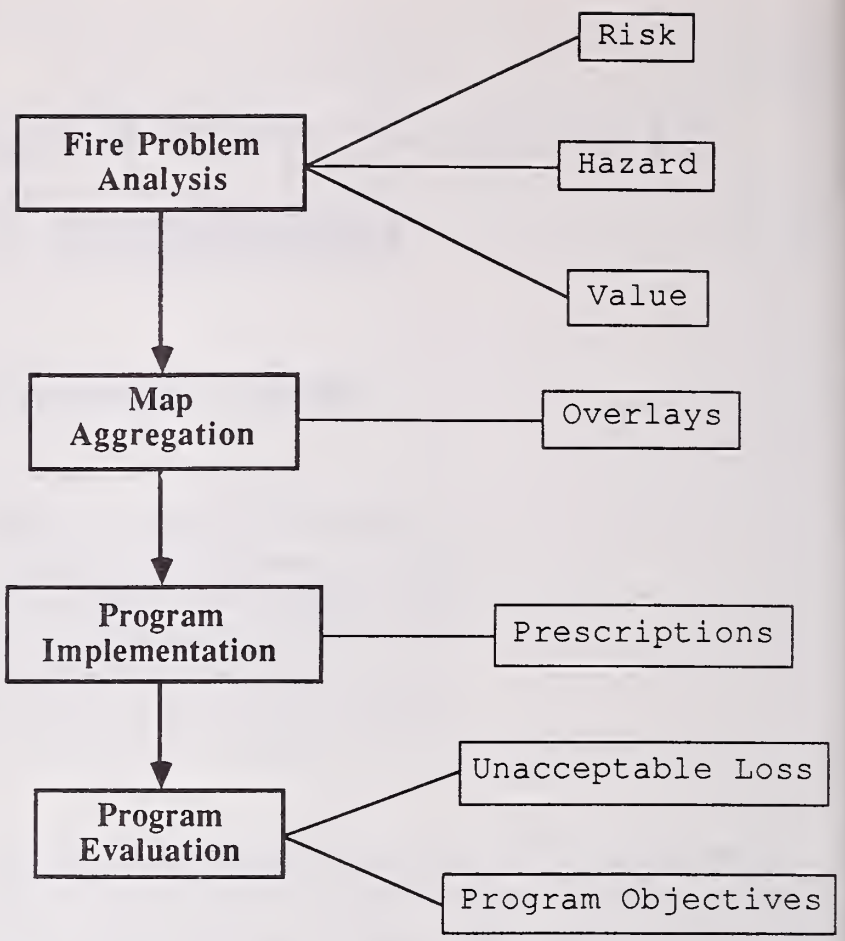


Figure 1.--The sequence of components (bold) and major sub-components contained in the prevention planning process.

Hazard analysis estimates resistance to control should a wildfire occur by evaluating wildland fuel conditions (a function of fuel type and climatic conditions) and slope classes. Ratings of resistance to control on contiguous areas are identified on a hazard map. *Value* analysis consists of inventorying, rating, and mapping potential value changes resulting from fire. Each analysis is performed independently, i.e., analysis of the potential for ignition is not affected by fire behavior analysis. Because of this independence, no particular order must be followed although each must be included in a comprehensive analysis.

After all analyses have been completed, the three maps are aggregated into one comprehensive map of the entire planning area. Currently, creation of maps remains a manual task; however, we envision for the future a utilization of geographic information systems for storage and manipulation of this spatial information. Fire prevention management compartments are delineated based upon risk analysis areas because ignition potential is the major concern of prevention. Each compartment receives a rating score for risk, hazard, and value from the analysis overlays. A final inventory summarizes and documents specific people activities, fuels, and values contained in each compartment. This aggregate map forms the data base for subsequent implementation, via program prescriptions, and follow-up evaluation.

From the combined inventory and aggregate map, specific action items are identified for each management unit. Prescriptions are written, incorporating each prevention action item; they cover duties to be performed, and their priority, under the

typical range (90th percentile) of fire conditions used in fire planning. Ninetieth percentile conditions are those fuel and weather factors where fire behavior begins to exceed the capability of initial attack forces to effect control. Contingency prescriptions may also be detailed for fire conditions that exceed the 90th percentile.

Evaluation of program effectiveness entails examinating prescriptions in relation to the extent and location of fire losses. Because the goal of prevention is a non-event (no fire), successful prevention efforts can only be assessed in terms of the numbers and severity of events that do occur, i.e., unacceptable losses. When unacceptable fire losses have not occurred, then, assuming average fire conditions, it may be possible to conclude that prevention efforts have been successful.

However, faced with losses considered unacceptable by land managers, a careful examination of those specific, damaging fire problems should identify the most prominent causes. Prevention personnel may refer to the program implementation document to verify completion of all prescribed tasks; failure to achieve specified tasks indicates a performance problem. Unacceptable losses occurring after tasks have been performed indicates that prescriptions may not be effective and need to be reconsidered. In the course of re-writing prescriptions, it may be necessary to re-analyze the risk, hazard, or value assessments associated with particular areas of losses.

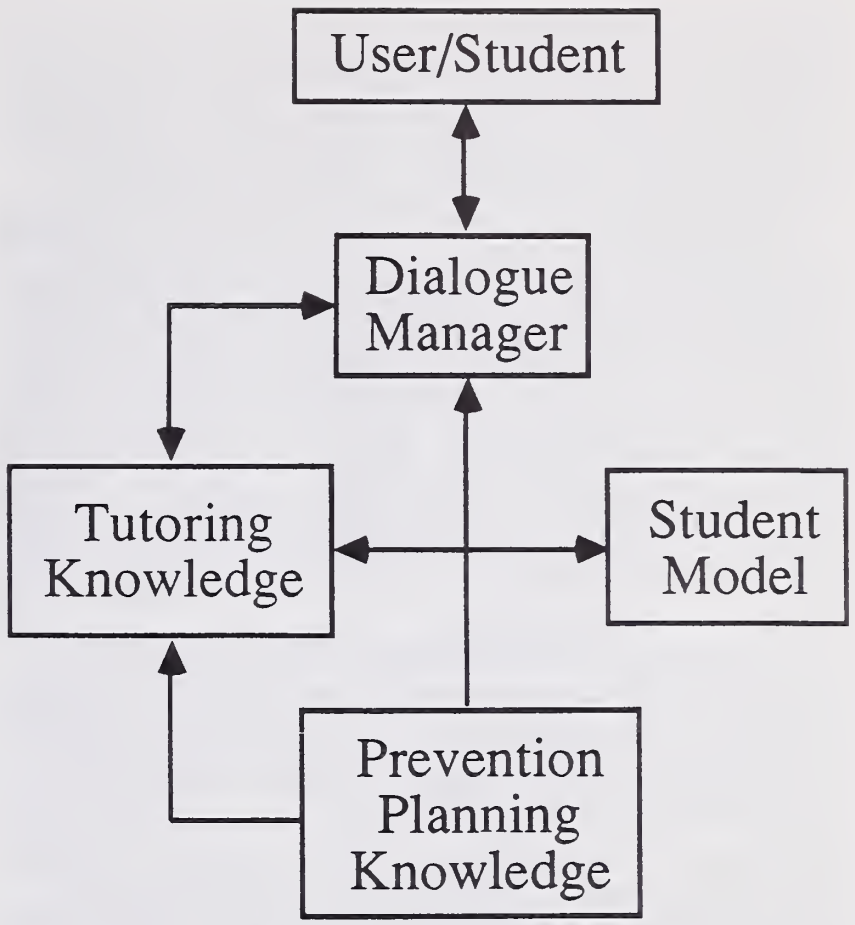


Figure 2.--Essential elements of an intelligent tutoring system for prevention planning. Arrows indicate the flow of information.

INTELLIGENT TUTORING SYSTEMS

Computer-aided instruction began in the 1950s with behavioral psychology's "linear program" view of instruction (Yazdani 1986). Under this perspective, direction toward some desired behavior is implied; reinforcing stimuli result from a successful response and direction correcting stimuli result from an incorrect response. Since this time, many other approaches have been used; most recently, knowledge-based systems have been utilized.

In addition to being effective for problem solving in forestry (Schmoldt 1987), knowledge systems possess some desirable properties for instructional uses. Expert reasoning and intuition can be represented in the system and conveyed to the student through tutored examples (example-driven problem solving) or declarative explanation (line of reasoning). The student is able to work many examples at varying complexity levels and at a comfortable pace without assistance from an instructor. MYCIN, a diagnostic expert system for infectious diseases (Davis et al. 1977), has been transformed into a tutor for medical students (Clancey and Letsinger 1981). Other tutors have been created for teaching: computer programming (Anderson and Reiser 1985, Johnson and Soloway 1985), natural language (Imlah and du Boulay 1985), geometry (Anderson et al. 1985), physics (White and Frederiksen 1986), and a pulp and paper process (Woolf et al. 1986). Merging computer-aided instruction and knowledge-based systems has resulted in intelligent tutoring systems.

Many of these ITSs have some common components; the arrangement of these components is illustrated in figure 2. Knowledge of the actual domain being taught must be captured and represented on paper or in a program, sometimes simultaneously at various levels of understanding (White and Frederiksen 1986). This knowledge is sometimes formally referred to as the "ideal student" model (Yazdani 1986). Strategies for tutoring the student in the particular domain must also be defined. These may include immediate or delayed error feedback, maintaining an actual student history (progress) model, and specifying the intensity of tutor and student interaction (dialogue management). To provide a comprehensive learning environment, the student must have access to large amounts of explanation, both for correcting erroneous behavior and promoting desired behavior. Specific implementation of these features will depend on the teaching task and types of students anticipated.

KNOWLEDGE ELICITATION

General

Our ITS approach differs from those described above by a desire to create a non-singular use system. Most ITSs contain a method of simulating or hypothesizing specific learning situations (examples) which serve as the focus of the learning environment. The prevention planning tutor being developed

operates with examples provided by individual users and presumably, reflects actual planning needs. In this way, we will create a knowledge-based system which solves actual ignition management problems and, at the same time, tutors fire prevention personnel in the techniques of the planning process.

The first step in development of the tutor involves creating a representation of knowledge about the planning process, i.e., the domain knowledge. Several prevention personnel on the San Bernardino National Forest are familiar with the process and have their own personal insights into the subtleties of fire problem analysis and program implementation. In addition, no individual within this group was previously involved in all aspects of the process to a large extent. Therefore, it became necessary to combine knowledge possessed by several experts and obtain consensus on the structure and operation of this planning process knowledge.

We selected the Delphi technique as a method for extracting and aggregating diverse perceptions of prevention planning knowledge. The Delphi technique is a general framework for arriving at agreement among individuals within a group on some particular item of interest. However, a number of serious drawbacks to this technique have been suggested previously (Shields et al. 1987): reliability of results, definition of consensus, and stability of group responses. In addition, the situation described in this paper requires the development of an extensive body of knowledge. This is an atypical use of the Delphi which is normally used to construct come scale or to estimate a point value. The authors propose a modified Delphi procedure which avoids these drawbacks and seems able to support the construction of a complex description of a planning process.

Standard implementation of the Delphi technique employs anonymous responses to questionnaires by each member of the group. Group interaction is minimized to avoid voice dominance by position or persuasiveness and to reduce the group pressure to conform (von Winterfeldt and Edwards 1986, p. 135). These questionnaires are repeatedly administered to the group, intermixed with feedback of questionnaire summaries, until some consensus has been reached. For our purposes, questionnaires would be too restrictive and inflexible for eliciting individuals' conceptual knowledge of a complex planning process. In addition, subsequent aggregation of separate expert's descriptions of highly interrelated knowledge would have been extremely difficult. A procedure which provided for progressive aggregation during the collection stage would be more efficient and require less effort. An alternative method of recording experts' opinions was sought.

The Cumulative Delphi

The following, general discussion of a modified Delphi for knowledge elicitation centers on the idea of a cumulative knowledge packet used in place of multiple copies of a questionnaire. Knowledge packets used in this study are more fully described below (see Application Specifics). Figure 3 illustrates

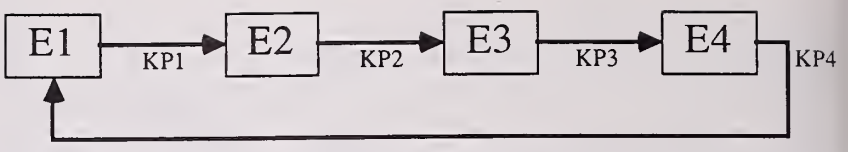


Figure 3. Routing of cumulative knowledge packets (KP1, ...) between experts (E1, ...) in the modified Delphi technique.

the interaction of experts and knowledge packets in this cumulative Delphi technique. Each E_i and KP_i refers to particular experts and knowledge packets, respectively. Preliminary, general discussions are initially held with all experts to identify components of the elicited knowledge and those most experienced in each component; these individuals are given positions E_1 and E_2. For each pass of the cumulative Delphi, the most knowledgeable experts are interviewed first.

A pass of the cumulative Delphi is completed for each knowledge component identified previously. An interview with E_1 produces KP_1 which contains: concepts describing the particular component, definitions of these concepts, relationships between concepts, and types of concept relationships. For our needs in terms of a knowledge base, these elements seemed to capture the essential aspects of the planning process; other applications of the cumulative Delphi may require different knowledge packet contents (see Discussion). Subsequently, KP_1 is given to E_2, and E_2 is asked to make any modifications to the knowledge packet which seem appropriate. These modifications are made and recorded in an interview setting. The revised knowledge packet is then presented to E_3 as KP_2. The routing of knowledge packets continues in this manner. When KP_4 from E_4 is presented to E_1, E_1 is asked to review the changes to KP_1 contained in KP_4. If the changes are acceptable, then KP_4 is installed as the initial representation of this component of the planning process.

The case has not yet arisen in which KP_4 is unacceptable to E_1. In the event of such a conflict, two solutions are possible. Another routing of knowledge packets through the experts (beginning with KP_4 and E_1) may mitigate most significant differences, leaving only minor discrepancies whose importance will generally be small in terms of an initial representation. Alternatively, a non-confrontational arbitration may be used to smooth divergent views, in which case, the authors may mediate some mutual agreement. When the domain being represented in an expert system achieves the property of consistent expertise (a property which Buchanan and Duda (1983) considered essential to effective development of an expert system), then large deviations from consensus should not be problematic or should be easily resolved by the above procedures.

The cumulative Delphi seems to mitigate most concerns expressed previously by Shields et al. (1987). The question of reliability of Delphi results in this application relies more on the form of this domain than on the cumulative Delphi technique itself. In the planning process description, unlike consensus value assignment, a second group of experts might arrive at a different representation, but it would be functionally similar to the previous one, provided the two groups were describing the

same process. Routing of a common document forces acceptance of major points, which should be identical between two Delphi groups, and facilitates non-confrontational discussions of smaller discrepancies. Consensus is specifically defined as acceptance of the final knowledge packet by the first expert; this definition may be extended to include acceptance by all experts if it seems necessary. The commonality attribute of the knowledge packet encourages stability in progress toward a rapid consensus. Potentially valuable group interaction is sacrificed for a less engaging, but apparently effective, form of detached cooperation.

Application Specifics

The initial step of the modified Delphi, as mentioned, was a general meeting of all four experts which took the form of an unstructured interview. The investigators first presented a detailed overview of expert systems, knowledge elicitation, and the project at hand; considerable discussion took place as the experts became familiar with ITS ideas and processes. The meeting then shifted to the first discussion of domain content.

This initial phase of elicitation was facilitated by the fact that the knowledge to be developed related to a systematic planning process whose elementary logic flow was known to all (including the investigators). The initial group meeting concentrated on achieving agreement on major planning process components and definitions. Although this went well, there was evidence of rank differences between experts influencing the contribution of some members; this reinforced our plan to solicit input from the experts individually.

The meeting also enabled the investigators to gauge potential input from each expert and establish the order of involvement. Expert One was not involved in development of the process but in its subsequent application by other units of the national forest. Expert One, thus, had a good, generic over-view of the process derived from helping others with implementation, and was the perfect candidate to initiate conceptual elicitation for each planning process component. Expert Two was directly involved with specific development of the planning process. He was utilized second in our cumulative Delphi, as he was the best candidate to fill in details of each component. Expert Three was able to visualize the planning process in generic, conceptual terms. He was proficient at reviewing the knowledge packet for each component, integrating concepts and specific application details. Expert Four was less involved in development of the process but has been involved in application. He was less conceptually oriented but represented the final, user step of planning process application.

Data collection during the group meeting was the same as during individual interviews. Both investigators took notes and the dialogue was tape recorded for subsequent review.

The first private interview had the investigators engage both Experts One and Two to develop the hazard analysis component (Expert One had little to do with actual development of this component). Each expert was presented with a block diagram of the entire planning process and also a diagram for the hazard analysis. The components of the planning process were blocked out and diagrammed after the initial (group) meeting. Recall of the analysis steps was initiated by referring to documentation from earlier prevention planning and the diagram. The documentation could not be utilized directly for this study because it represented a product (a completed fire prevention plan for a specific locale) instead of the process (many of the analytical steps were hidden behind final plan conclusions). The recall itself proceeded from general points to detailed steps, sometimes re-ordering the step sequence. The tape recording of the first interview again reinforced the need to work with the experts one at a time because differences in rank occasionally influenced input.

Risk analysis elicitation illustrates the individual interview sequence. The investigators met with Expert One; he received a copy of the general block diagram developed from the group meeting. Using the diagram and copies of documentation from earlier planning cycles, he began recall of the steps of this analysis.

The input was subsequently reduced to (1) concepts and (2) relationships by the investigators through use of notes and tape-recordings. Concepts and tasks were identified from the dialogue and linked with non-directional arrows; these were verified by listening to the tape. The iterative process of working back and forth between hard copy and tape was also followed for listing definitions and relationships. As definitions for each entry on the graph solidified, relationships became readily apparent. Several general relationships were specified (fig. 4), and connecting lines became directional arrows. The risk analysis component was then graphically summarized on one page, identifying concepts, tasks, sub-components, attributes, antecedents, products, and points where documentation is collected (fig. 4). The graph, plus a glossary (fig. 4; insert) of all items in the graph, represented Knowledge Packet 1 for the risk analysis component.

Knowledge Packet 1 for risk was then presented to Expert Two. This packet provided a highly-structured interview schema for dialogue with subsequent experts. The investigators stepped through the packet item by item with the expert, clarifying anything that seemed unclear. Questions posed by Expert Two indicated aspects of graph components which needed clarification or modification. Several definitions were changed, a portion of the graph was removed, and one additional attribute was added to ignition potential activity.

Knowledge Packet 2 resulted from the changes. It was presented to Expert Three who suggested minor modifications to several definitions. Because of Expert Three's analytical abilities, he found the graphical presentation of concept and processes very natural and comprehensible. The resulting knowledge packet was presented to Expert Four who had essentially no changes to make.

The same cumulative Delphi sequence was utilized for the other components such as hazard analysis, value analysis, map

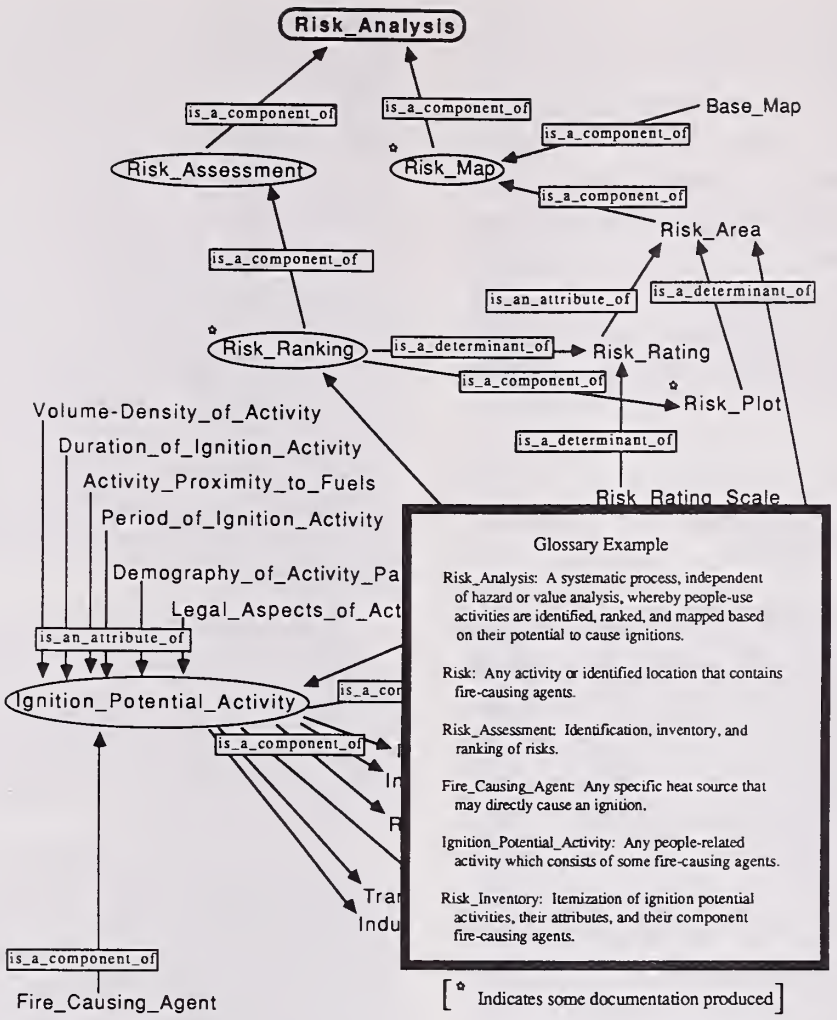


Figure 4.--Concept graph for the risk analysis component of the prevention planning process. Concepts, tasks, and their relationships (arrows) are included. A portion of the graph is obscured by the insert which contains several example definitions from the glossary for this graph.

aggregation, and program implementation. Experts Two and Four focused mainly on the terminology and definitions of the knowledge packets with less interest in the relationships. Expert Three was able to identify relationships that were incorrectly specified or should not be present at all; he used terminology definitions for purposes of understanding and correcting the concept graph. All modifications to Knowledge Packet 1 that occurred in the routing process have been of two types: (1) changes resulting from misconceptions on the part of the investigators, or (2) minor changes to definitions or graph relationships. Neither of these represented significant modifications to the original knowledge packet from Expert One.

DISCUSSION

Products of our knowledge elicitation efforts appear sufficiently comprehensive for actual construction of the tutor (in which we are currently engaged). In terms of the concept graph, all components, their dependencies, and their relationships have been enumerated. A textual description of this information also resides in the attached glossary. In addition, we have tape-recordings of all discussions which may contain minor points and examples not captured by the knowledge packets. The task that remains is representation of that knowledge in a form that permits learning the process and formulating actual prevention programs.

On the basis of preliminary work with knowledge elicitation in this study, a number of interesting observations can be made. Due to the previously unrecorded nature of prevention planning process knowledge, our efforts to date have identified and scrutinized what is known about the planning process, and have contributed significantly to its understanding and formalization. Specific planning process tasks and fire prevention concepts have been isolated and their meanings solidified. There were subtle, yet significant, aspects of the process which previously had not been realized by one of us (Bradshaw) who was very familiar with the planning process. Areas of subjective knowledge used by the experts at various steps in planning have been identified; this judgmental component will be formalized in subsequent stages of this project. Even should a tutoring system not be developed from this study, advances in understanding and formalizing the process make the elicitation task itself quite worthwhile.

The sequenced elicitation approach used here uncovered some areas of the planning process where guidance could be useful in making judgments, especially in quantifying previously subjective judgments. The experts agreed on benefits of

such an approach, but related difficulties they experienced when trying to quantify judgments. Interestingly, the difficulties seemed to arise from a desire to "count" instances of a sub-component (e.g., the number of dwellings in a prevention compartment) rather than numerically rate attributes of the sub-components in the compartment (e.g., volume-density of dwellings, duration of associated ignition activity, period of activity, demography of participants). The change to be incorporated in the tutor is to guide attribute ratings for sub-components instead of dealing solely with counts or frequencies.

Even though other types of knowledge have not been addressed in this study, the general cumulative Delphi approach could be universally applied. Knowledge in this application consists of tasks and concepts, a dependency list of items to accomplish and/or ideas to comprehend. The form and details of the knowledge packets reflect this usage. If an investigator were eliciting decision rules (inferences) from experts, different knowledge packets would be necessary. In such an instance, packets might contain actual rules elicited and their justifications, or they could be responses/solutions to real-world examples, which could subsequently be used to construct inference rules. Irrespective of the type of knowledge, content of the packet should be as equally detailed as the level of knowledge required in the system being developed.

In addition to the type of knowledge and level of detail, several other aspects of knowledge packets should be addressed. Some consideration should be given to experts' capabilities to understand the format of the packet. As we discovered in our experiences, not all individuals were equally comfortable with the format of our knowledge packets. Expert Three seemed very comfortable with, and readily grasped, the concept graph presentation; Expert Four was less analytically inclined. Also, decomposition of the entire problem space into smaller problems means that less information needs to be included in a single packet. This is an axiom of knowledge system development and has been reinforced by our experiences and so deserves mention here. Complexity will be reduced, and a single packet will be less likely to overwhelm an expert. In addition, it may be useful to have two tape recorders present during interviews. One would be used for current recording, and the other for replaying specific comments by other experts. This is valuable during points of dissension in which investigators are unable to recall exact details of a previously interviewed expert's arguments. Preliminary group or individual interviews can provide guidance for making these decisions.

Although using multiple experts makes the knowledge elicitation bottleneck of expert system development more pronounced, each expert has some personal intuition and perspective which has proven valuable to the overall knowledge collected. Cumulative Delphi methods have facilitated the capture and aggregation of these diverse opinions. On several occasions, an expert has discussed particular details which would not have been proffered in a group situation. Individuality seems to have been preserved while realizing group consensus. It appears that the knowledge packet approach, especially when walking each expert through a packet, provides sufficient interaction of ideas without disruptive confrontation or dominant role playing. Later, experts required very little time to review each packet because of the level of completeness already achieved. Any additional time consumed for multiple experts would otherwise have likely been spent in revising material, re-interviewing a single expert, and possibly restarting the elicitation process. The visual aid quality of the knowledge packet also helps application-oriented people (experts) make the transition from work-related experience to verbalizing abstract concepts.

For expert system development where several experts are available, it seems prudent to exploit their separate, private knowledge. A methodology has been outlined which induces such elicitation and facilitates its consentaneous synthesis.

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Nonlinear Learning Curves and Forest Management Planning

Dennis P. Dykstra[1]

Abstract.--Learning curves have been used since the 1930's to account for long-cycle learning in production processes. They have seldom been used in forestry because the traditional learning-curve model fails to account for variables other than the cumulative number of units produced. This paper reviews the theory of learning curves and suggests a new learning-curve model suitable for complex forest operations in which long-cycle learning may be important.

Good estimates of production rates for forest operations are essential for accurate forest management planning. Traditionally such estimates have been made by developing regression equations from studies of existing operations and then using those equations to estimate production rates for planned operations in areas of similar timber and terrain conditions. One important shortcoming of this method is that it fails to account for long-cycle learning and forgetting effects that can significantly influence production rates of operations such as logging, which can be affected by training or by seasonal changes such as heavy rains or snowfall. Learning effects can be particularly important in developing countries, where policy decisions may include consideration of whether to adopt new technology or to emphasize more traditional methods.

Learning Curves

It has been demonstrated for a wide variety of production processes that, as an individual worker or crew continually repeats the process, productivity shows gradual and predictable improvement (Yelle 1979). For instance, when a person begins planting trees for the first time, that individual is likely to proceed slowly at first, working carefully but making many unnecessary and time-consuming movements. After a few days or even hours, the worker becomes more comfortable with the process and settles into a faster and more efficient working pace.

Learning-curve theory postulates that the time required to produce a fixed quantity of output (e.g., the time required to plant 1,000 seedlings) will be reduced for quite some time at a more or less continuous rate, until eventually a "working plateau" is reached, beyond which essentially no further improvement can be expected without additional investment such as training in improved methods or the purchase of new planting equipment. This general concept is illustrated in figure 1. Note that a fixed *rate* of reduction in the time to produce one unit (e.g., a reduction of 0.1% per seedling in the time required to plant a seedling) corresponds to the familiar negative exponential or "reverse J-shaped" curve.

From observations on improvements in production processes, Wright (1936) hypothesized that the rate of improvement for a particular production process could be measured and used reliably to predict future production rates. Wright's model assumed that improvements during the learning phase would proceed at a constant rate. Repeated tests of the model since that time have confirmed that this assumption is satisfactory under a wide variety of operating conditions (Yelle 1979). Wright's model can be stated as follows:[2]

$$Y_N = \alpha N^{\beta} \qquad [1]$$

where

Y_N= the time required by a worker or crew to produce the Nth unit in a series (e.g., to plant the Nth seedling);

α= an estimate of the time required to produce the first unit in the series (thus, α is an estimator of Y_1);

β = a constant that measures the rate at which the time required to produce a single unit changes relative to the cumulative number of units produced.

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[2]*Wright's original model was based on the cumulative average time (i.e., the total time required to produce the first N items, divided by N). Later Crawford (1944) suggested that the unit model specified in equation [1] would be more reasonable for certain types of production processes. This latter model seems generally more applicable to forest operations than Wright's cumulative-average model.*

In this "log-linear" model of productivity improvement, the parameter β is often referred to as the "learning index." If $\beta < 0$ then productivity is improving; if $\beta = 0$ then productivity is constant; and if $\beta > 0$ then it is worsening.

Another quantity commonly used to characterize learning curves is the "progress rate" (called the "learning rate" by many authors), calculated as $\sigma = 2^{\beta}$, where σ is the expected time required to produce unit $2N$, expressed as a fraction of the expected time to produce unit N. A learning curve with $\sigma = 0.8$ is often referred to as an "80% curve." Lower values of σ imply faster rates of productivity improvement. In my experience, having taught the concept of learning curves to university students in both North America and Africa, I have found that this is the opposite of what many people assume when they hear the term "learning rate." Therefore, although σ is defined as the learning rate by many authors, I prefer to call it the progress rate, and to define the learning rate as $\delta = 1 - \sigma$. In this definition, a higher learning rate implies faster improvement in productivity, which is consistent with popular usage if not with standard usage in the terminology of learning-curve theory.

Learning Curves and Forest Operations

The fact that productivity improves over time in forest operations has long been recognized intuitively by operations managers, but there have been few attempts to measure this improvement or incorporate it into operations planning. The most common approach in productivity studies of forest operations has been to assume that the process under study has already reached the working-plateau phase, so that no adjustment for improvements in productivity over time is necessary. If this assumption is correct, then there is no difficulty; but if the assumption is wrong, then productivity will be underestimated and appraisals (for instance, to determine stumpage prices) will overestimate production costs.

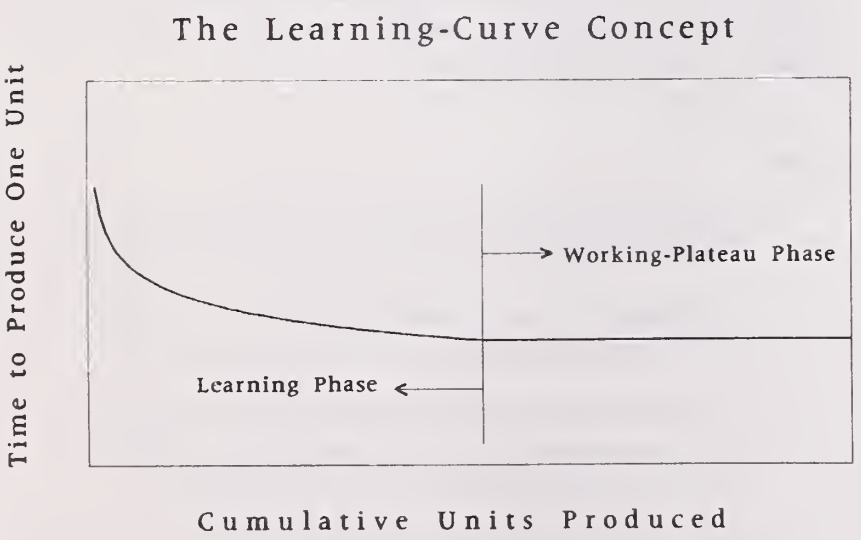


Figure 1.--The learning-curve concept, showing the "learning phase", during which the time to produce a fixed quantity of output is gradually and continually reduced, and the "working plateau phase," during which average output per unit time is essentially constant.

Although the learning-curve concept has not been widely used in research on forest operations, several studies are worthy of mention. As a result of experience with machine felling in eastern Canada, McNally (1977) developed a simple procedure to take into account the effect of on-the-job training on productivity. McNally's conjecture was that a new machine operator would require about 6 months to achieve the productivity of an experienced operator. During the training period, productivity could be expected to increase steadily (i.e., at approximately a constant rate), beginning with a production rate about one-third that of an experienced operator.

Around the same time, Garland (1979) initiated work designed to measure improvements in productivity associated with the training of chokersetters. Garland's primary interest was in the tradeoffs among the training investment, frequency of job changes (i.e., job satisfaction), and increased productivity. In the course of this and later work (Garland 1981), he measured learning curves for several crews of chokersetters, reporting average learning rates of around 10%. This means that the expected time required for a crew to accomplish the chokersetting task for the 200th turn of logs would be about 10% less than the time required by the same crew to accomplish the same task for the 100th turn of logs, all else equal. Garland's work also suggested that for the crews in his studies, a working plateau would be achieved for which chokersetting times would average approximately 56% of the time required to set chokers on the first turn of logs.

A recent study by Greene and others (1987) found that felling-machine operators using an interactive simulation model as a training device "learned" at rates significantly below those reported by Garland. The learning rate for the operator who improved the most during the study was 3.3%. Reduced learning rates (i.e., nearer to 0%) are to be expected in mechanized operations where machine-pacing largely determines the rate of production; hence the much more rapid rate of productivity improvement in Garland's chokersetting studies.

Learning Curves Under Variable Conditions

Learning-curve theory was originally developed for "long-cycle" factory operations, and has been most commonly used in that type of production environment. Long-cycle operations are those that require significant time to complete, such as the construction of an airplane. Most forest operations would also be classified as long-cycle operations, as opposed to short-cycle operations such as pulling lumber off a conveyor chain, where each operation requires only a few seconds.

In the controlled environment of a factory, conditions remain relatively constant from day to day, so it seems sensible that the primary variable considered to influence production

rates is the number of long cycles that have been completed during a production run (e.g., the number of airplanes produced). Conditions associated with forest operations, on the other hand, are highly variable. Although the total number of tree seedlings planted by an individual may influence the time required by that individual to plant the next seedling, many other factors can influence that time as well. A few examples include slope steepness, soil type, the amount and character of ground cover, weather conditions, and the payment system (e.g., hourly wage versus a piece rate). Forest operations, in this sense, can be thought of as "more complex" than factory operations. Because learning-curve theory fails to account for variables other than the cumulative number of units produced, learning curves have seldom been used in forest productivity studies.

A New Learning-Curve Model

To account for the many variables that influence productivity in forest operations and yet simultaneously consider the effect of cumulative production on productivity, it seems reasonable to propose the following learning-curve model:

$$Y = \alpha_0 + \alpha_1 X_1 N^{\beta 1} + \alpha_2 X_2 N^{\beta 2} + \ldots + \alpha_m X_m N^{\beta m} + \alpha_{m+1} N^{\beta m+1} \quad [2]$$

where

Y = the dependent variable to be estimated (e.g, the time required to fell the *N*th tree),

α_j = a regression parameter ($j = 0, 1, \ldots, m+1$) measuring the contribution of variable X_j to variable Y,

X_j = an independent variable (e.g., dbh of the *N*th tree),

N = the cumulative number of units produced (e.g., the number of trees felled),

β_j = a regression parameter ($j = 0, 1, \ldots, m+1$) measuring the rate at which the contribution of variable X_j to variable Y changes in proportion to the cumulative number of units produced.

Except for the nonlinear terms $N^{\beta j}$ and the m+1 term, equation [2] looks exactly like the typical regression model used to estimate the time required for an individual forest operation, such as tree felling. Parameter α_0 accounts for any fixed times in the production of a single unit, and the α_j ($j = 1, 2, \ldots, m$) measure the individual contributions of the independent variables to the overall estimated time for the operation. The final term in the model looks exactly like the traditional learning curve in equation [1]. This model is thus a hybrid of the traditional learning-curve model and the traditional operations-productivity model. It permits explicit estimation of two types of learning:

(a) overall learning associated with the entire operation (the m+1 term);

(b) learning associated with each independent variable (the $N^{\beta j}$ terms).

An Empirical Test

In 1982 a research project undertaken by Migunga (1982) and reported in Migunga and Dykstra (1983) provided an unusual opportunity to measure learning rates for chainsaw felling in Tanzania. Migunga's research was designed to compare the cost of cutting plantation timber with crosscut saws versus the cost of using chainsaws. The chainsaw component of the study offered a good chance to test learning curve theory because the workers involved in the study had no previous experience with chainsaws (although they were experienced in the use of crosscut saws).

The study was conducted in a plantation of *Pinus radiata* D. Don at the Training Forest of the University of Dar es Salaam near Arusha in northern Tanzania. The trees were 16 years old and were being clearfelled because of damage by the fungus *Dothistroma pinii*. Before initiating the study, the workers were given a week's training in safety, operation, and maintenance of the chainsaws. Then a detailed time study was commenced in which every aspect of the cutting operation was timed with stopwatches.

Like many production studies of forest operations, the cutting study was divided into work elements (felling, limbing, measuring, and bucking). For each element the productive time and any delay time were recorded to the nearest 0.01 minute. Data on independent variables expected to influence production rates were also measured and recorded. These included, for each tree, the diameter at breast height (dbh) in centimeters, total tree height (H) in meters, number of logs cut from the stem (NLogs), and the volume of each log (V) in cubic meters. The 221 trees involved in the chainsaw study averaged 31.6 cm (12.4 in) in dbh with an average total height of 26.2 m (86 ft) and an average total merchantable volume over bark of 1.05 m^3 (about 160 board feet). The volume harvested from the compartment averaged 172 m^3/ha (about 10.5 mbf/ac).

Traditional Regression Analysis.--Figure 2 shows a time series of productive (i.e., delay-free) felling times for the 221 trees involved in the chainsaw study (in this paper, the term "felling" is used to refer to the entire cutting operation, including felling, limbing, measuring, and bucking). Although there appears to be a slight downward trend toward the right side of the figure, there is so much variability about this trend that any simple characterization seems unlikely to be useful. The approach used by Migunga to analyze the data was that of the traditional operations-productivity model, which assumes that the crew has already reached the "working plateau" phase (i.e., learning no longer occurs). The dependent variable was productive felling time in minutes per tree. Independent variables tested for inclusion in the regression model were dbh, dbh^2 (a surrogate for basal area), H, NLogs, and V. Variables accepted

for inclusion had to be statistically different from zero with a maximum error probability equal to 0.05. Migunga's final model, selected using ordinary least squares, was as follows (numbers in brackets below the regression coefficients are the standard errors of the respective coefficients):

$$T = \underset{[2.913]}{8.589} - \underset{[0.185]}{(0.450)(dbh)} + \underset{[0.0027]}{(0.0141)(dbh^2)} + \underset{[0.351]}{(0.897)(NLogs)} \quad [3]$$

$R^2 = 0.64$, overall $F = 131.3$, $n = 221$

Traditional Learning-Curve Analysis.--Although Migunga's analysis would ordinarily be considered quite satisfactory, because of the fact that the study involved workers with no prior experience in chainsaw felling, it seemed reasonably certain that some improvement in skill levels ("learning") *had* taken place during the study. If true, this would imply that one of Migunga's basic assumptions, that the working plateau had been reached prior to the beginning of the study, was violated. We therefore decided to see whether the traditional learning-curve model would explain any of the variance in the data. To do this we used the logarithmic transformation of equation [1] to fit the traditional learning curve as follows:

$$\log(T) = \underset{[0.129]}{3.375} - \underset{[0.029]}{(0.199)(\log(N))} \quad [4]$$

$R^2 = 0.18$, overall $F = 48.6$, $n = 221$

Both of the parameter estimates in equation [4] are significant with error probabilities less than 0.001. Assuming the parameters are free of bias, the log-linear equation can be written in a form equivalent to that of equation [1]:

$$T = (29.228)(N^{-0.199}) \quad [5]$$

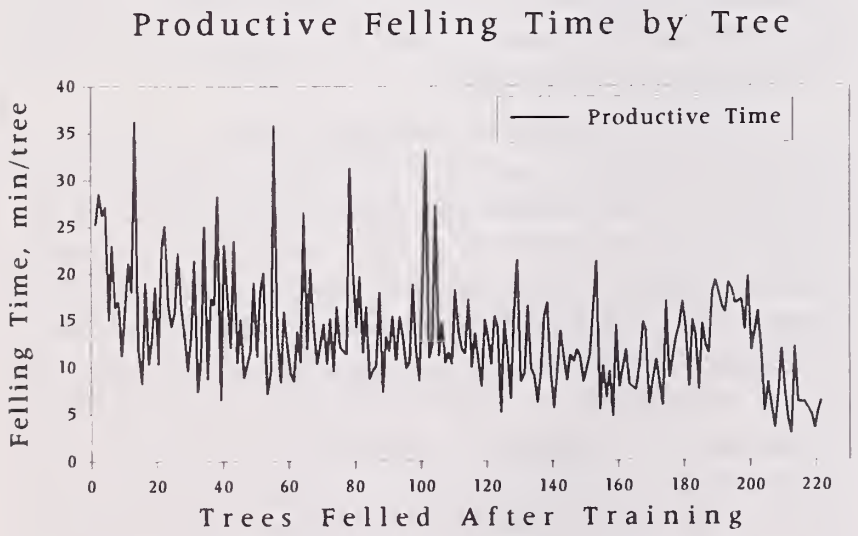


Figure 2.--Time series showing the productive felling time (the total of felling, limbing, measuring, and bucking times but not including delay times), in minutes per tree, for the 221 trees involved in the chainsaw-felling study of Migunga and Dykstra (1983).

From the definition of the learning rate, δ, it follows that

$$\delta = 1 - 2^{-0.199} = 0.13 \quad [6]$$

In reflecting on the results of this traditional learning-curve analysis, we concluded (Dykstra and Migunga 1986) that equations [4-6] were of little practical use. The analysis assumes that the only variable exerting an influence on cutting productivity is the cumulative number of trees felled; independent variables such as dbh and NLogs are assumed to have no effect. If such independent variables actually do influence cutting time per tree (and equation [3] suggests rather strongly that they do), then the traditional learning-curve analysis of equations [4-6] would only be useful if the magnitudes of the independent variables were *constant* for all trees felled, *both during the study and on future operations for which production rates are to be estimated by the equations*. But if that were the case, then equation [3] could not have been estimated at all. Clearly, then, the traditional learning-curve approach is too restrictive for application in this type of logging productivity study. Furthermore, it is evident from this discussion that equations [4]-[6] may either overestimate or underestimate the learning effect, depending upon whether trees felled later in the study were larger or smaller than those felled earlier in the study.

Modified Learning-Curve Analysis.--Although Migunga and I initially formulated the model of equation [2] in 1982, for several years we were unable to test it numerically because the only computer to which we had access was a Hewlett-Packard[3] Model 85 microcomputer with 32 Kbytes of main memory, programmable only in BASIC. A major difficulty with the model of equation [2] is that it is intrinsically nonlinear; there is no way to transform it into a linear approximation (as can be done with the log-linear model of equation [1]). The HP-85 microcomputer was capable of calculating the linear regressions of equations [3] and [4] for 221 observations, but we were unable to program it to run a nonlinear regression analysis for the model of equation [2] because the memory requirements, even for a small subsample of the 221 observations, far exceeded the machine's capacity of 32 Kbytes.

Recently I acquired an IBM PC/AT[3] microcomputer with 1 Mbyte of main memory and an 80287 numeric coprocessor. Using this computer with the nonlinear least-squares option of the Micro-TSP[3] software package (Hall and Lilien 1987), I was able to fit the model of equation [2] to the 221 data points from Migunga's felling study. The result was the following regression equation. Convergence was achieved by Micro TSP after 13 iterations and required approximately 83 seconds on the IBM PC/AT.

$$T = \underset{[0.0688]}{(0.4389)(dbh)} \quad \underset{[0.0749]}{(N^{-0.2231})} + \underset{[0.00105]}{(0.00452)(dbh^2)} + \underset{[0.3040]}{(0.7156)(NLogs)} \quad [7]$$

$R^2 = 0.71$, overall $F = 174.7$, $n = 221$

[3]The use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by Northern Arizona University or the U.S. Department of Agriculture to the exclusion of others that may be suitable.

The four parameter estimates are all significantly different from zero with maximum error probabilities of 0.02. Comparing the model of equation [2] with the fitted results in equation [7], note the following:

1. the constant term was not significantly different from zero and has been dropped;
2. the overall learning effect (term m+1 in equation [2]) was not significantly different from zero and has been dropped;
3. the only significant learning effect corresponding to the independent variables was that associated with dbh. This suggests that the cutters' skill improved over time in proportion to the number of trees cut, but only with respect to the variability in cutting times explained by dbh.

Figure 3 provides a comparison of cutting times estimated with equation [7] to the observed cutting times for the study (the "envelope of observations" has been drawn by joining peaks from the time series in fig. 2). Much of the variability in the original time series has clearly been captured by equation [7], as has the general downward trend in the data.

Figure 4 compares the traditional learning curve of equation [5] with that of equation [7] plotted for the average values of dbh (31.6 cm) and NLogs (4.2) encountered during the study. It is apparent from the chart that the traditional learning curve overestimates the learning effect (i.e., the traditional curve is steeper than the nonlinear learning curve). From a cursory look at equations [5] and [7], this result may at first seem surprising. The learning index of equation [5] is -0.199, corresponding to a learning rate of 13%, whereas the learning index of equation [7] is -0.223, corresponding to a learning rate of 14%. Why, then,

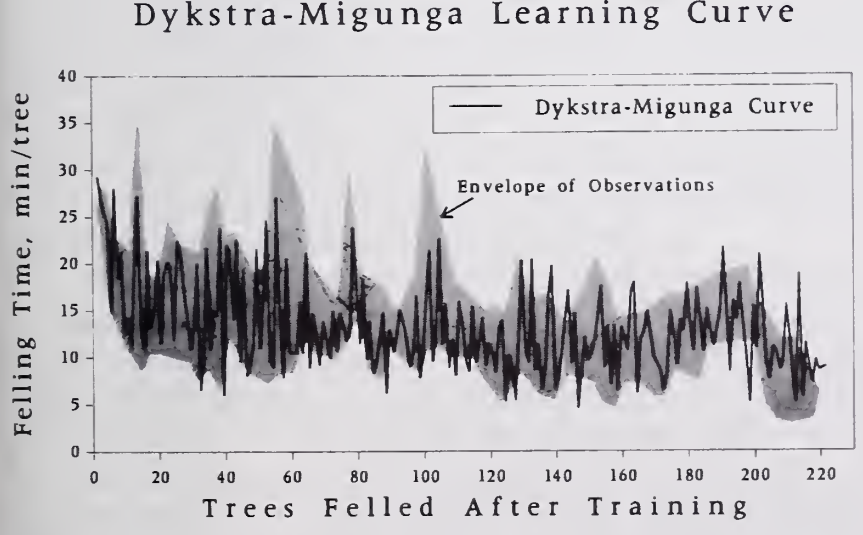


Figure 3.–Comparison of the actual time series of observations ("envelope of observations") to cutting times estimated with the nonlinear learning-curve equation.

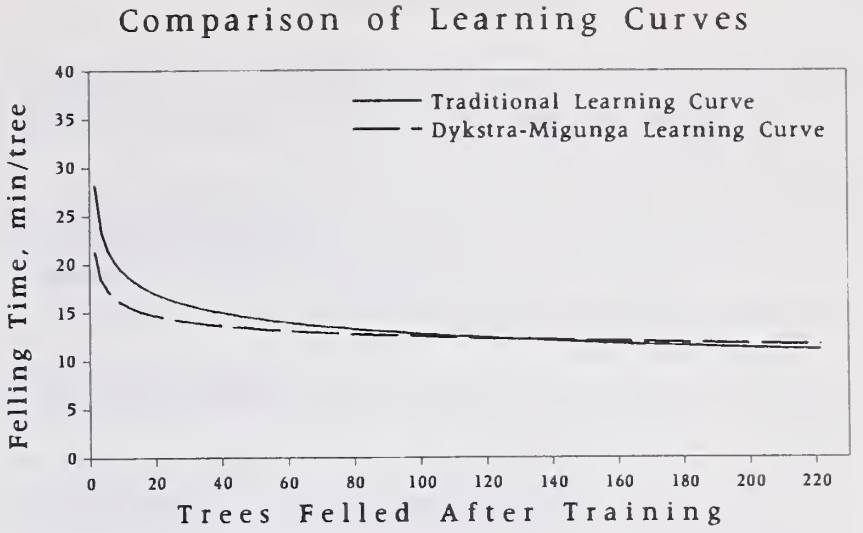


Figure 4.--Comparison of the traditional learning curve for the felling time study with the nonlinear learning curve fitted to the Dykstra-Migunga model and plotted with the average values of the independent variables measured during the study. The traditional learning curve overestimates learning because by chance the trees cut later in the study were somewhat smaller than those cut earlier.

is the traditional learning curve the steeper of the two? The answer is that the learning rate of equation [7] is associated only with dbh and not with the entire equation. Therefore, the improvement in skills measured by equation [7] corresponds only to the contribution of dbh to the explanation of variance in the dependent variable. An inspection of the time-series data for Migunga's study shows that some of the apparent "learning" measured by the traditional learning curve is due to the fact that the average dbh of trees felled during the study declined slightly as the study progressed. Because the more flexible model of equation [7] considers the effect of independent variables as well as that of the learning trend, it is more likely to avoid such spurious correlation effects.

Concluding Remarks

The nonlinear learning-curve model proposed in this paper as a basis for measuring improvements in skills over time shows considerable promise for applications in long-term planning and control of forest operations. As a hybrid model combining elements of the traditional learning curve with the regression model traditionally used in studies of forest operations, it permits learning rates to be measured while also permitting measurement of the contributions of independent variables to production rates and costs. The primary disadvantage of the nonlinear learning-curve model is that it is intrinsically nonlinear in form, and therefore requires access to a computer and software capable of fitting nonlinear regression equations.

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An Application of FORPLAN for Regional Timber Projections

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Abstract.--Timber availability was forecast over a 100-year period for one of Pennsylvania's more valuable hardwood regions using the USDA Forest Service FORPLAN model. The eight-county region was found to have a sawtimber production capability that could more than triple during the next 60 years. Age class distributions would also become more balanced, thereby tempering cyclical harvest patterns.

Timber resources are gaining increased attention within northeastern United States. In part, this relates to the gradual transition of these intermediate aged hardwood forests to a more mature and marketable status. Allied with this change has been a moderate increase in the output of forest products and in the export of logs and lumber to foreign markets. The renewed interest in timber may also be attributed to a general search for alternate means of revitalizing Northeastern economies. Whether these forests can serve as a catalyst to development will depend on the long term production capability of the forests and the economic advantage available to resident industries.

In Pennsylvania, forests extend over 16.8 million acres, representing 58%of the state. While Pennsylvania ranks only 33rd in land area among all states, it is 12th in total timberland (forestland producing or capable of producing crops of industrial wood of more than 20 ft^3/ac/yr, and not withdrawn from timber utilization). This includes 20 billion cubic feet (bcf) of hardwood growing stock; more than any other state in the country. About 50% is in sawtimber stands, representing 42 billion board feet (bbf) of hardwood sawtimber (Powell and Considine 1982). The size and stature of this resource base is also reflected in lumber production, with Pennsylvania ranked first among all states in hardwood lumber output during 1986 (National Forest Products Association 1987).

The State's present forest developed with only a minimum degree of forest management. Prior to 1880, timber harvesting was largely directed toward the more accessible pine and hemlock stands. Major clearcutting followed during the period 1880 to 1900, in tandem with the development and use of railroads for logging and hauling. By 1920, the remaining virgin and partially cut softwood stands had been clearcut (Marquis 1975). Much of this forest gradually regenerated to hardwood types, with the primary management effort directed to fire protection. Now, large portions of the forest are reaching harvestable age.

The impending maturation of a large proportion of the state's timberland has led to some speculation that the timber production upswing experienced in Pennsylvania at the turn of the century could be repeated. However, neither the short term nor the long term productive capability of the major timbersheds have been quantified. The dynamics of forest development and management need to be explored in terms of their impact on future timber yields and forest structure.

A series of studies was initiated by Penn State's School of Forest Resources to evaluate the timber availability within one of the State's key forest regions and to assess the current structure of the region's forest products industry. Two timber production models were developed to determine the potential long term flow of timber products from the region's public and private ownerships. This paper describes the design and results of the second regional model.

Description of the Study Region

The Allegheny Region, an eight-county area located along the northern tier of Pennsylvania (fig. 1), was selected for study because it comprises one of the State's more valuable timbersheds. The region is 84% forested and contains the largest per acre and total growing stock volumes of any of the eight forest survey units in the state (Powell and Considine 1982). It also includes over 20% of the state's timberland, about 3 million acres. The more valuable northern hardwood types dominate, representing 69% of the timberland. Upland oak types are found along the southern portion of the region and comprise 21% of the timberland area. Nearly 55% of the acreage was classified as

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sawtimber stands, with 37% in poletimber and 7% in seedling/sapling (Considine and Powell 1980).

Timberland within the region is actively managed by both the public and private sectors. Forty-two percent of the timberland was under public management, organized by the U.S. Forest Service, the Pennsylvania Bureau of Forestry, and the Pennsylvania Game Commission. Over 17% of the timberland was managed by the forest products industry and an additional 10% was owned by nonforest-based industries. The remaining 31% was owned by farmers and other private non-industrial classes (Considine and Powell 1980). Over 60% of the private timberland was situated on tracts exceeding 200 acres in size, with 45% in tracts over 1,000 acres. An active forest management attitude was prevalent within these properties, with 72% of the private timberland controlled by owners who had harvested in the past (Birch and Dennis 1980). Owners who had not harvested in the past most often cited immature timber as their primary constraint.

A sizeable forest products industry was identified within the Allegheny Region (Westman et al. 1985). In 1981, there were 480 forest product processors within the region, comprised of 356 logging contractors, 89 primary manufacturers, and 33 secondary manufacturers. Sawmill consumption of logs was estimated at 160 million board feet (mmbf), Doyle scale, per year. The value of shipments from the forest products industry in that year was $366 million. Nearly 4,000 full-time equivalent workers were employed by this industry; representing 15% of the total employment within the region's manufacturing industries.

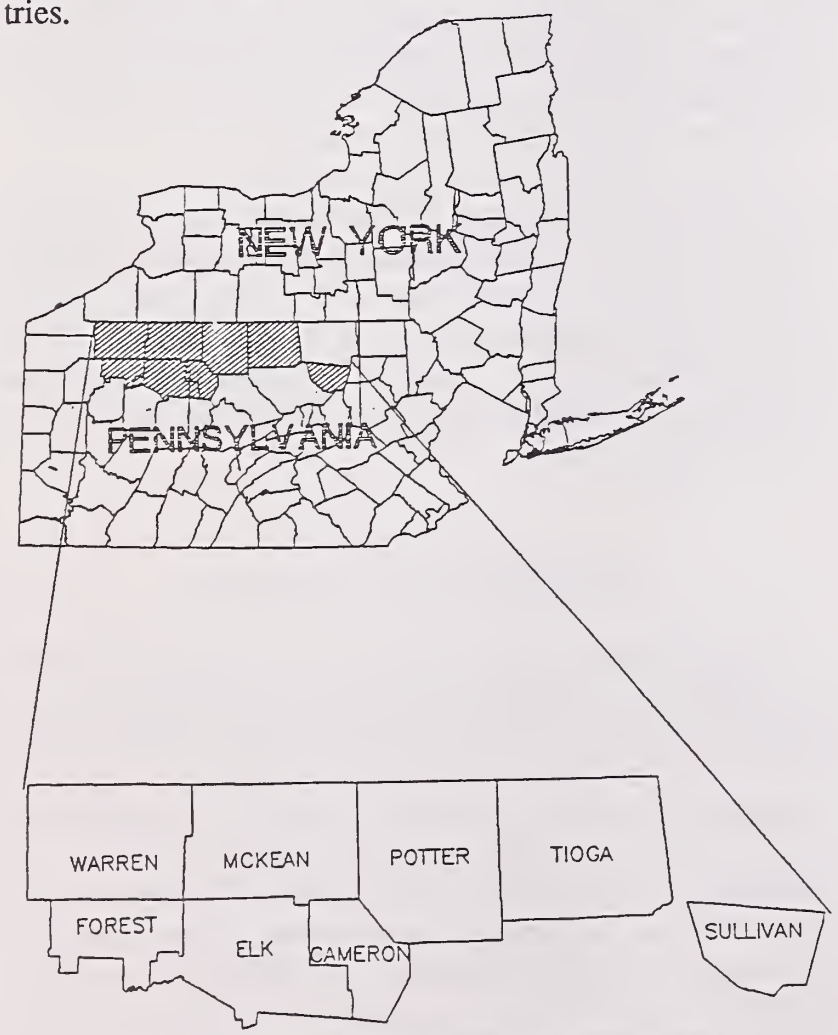


Figure 1.--The Allegheny Region of Pennsylvania.

An initial study of sawtimber availability in the Allegheny Region by Strauss and McWilliams (1987) provided a starting point for timber assessments. The TRAS stand projection model (Larson and Goforth 1974) was used for estimating sawtimber availability over a three decade period, 1980 to 2010. Stand size distributions were modified within the TRAS model by including the forest management strategies of the region's public and private ownerships as an integral component of the model (McWilliams 1985). Model forecasts indicated a potential doubling of sawtimber harvests, to an average annual level of 425 mmbf (International 1/4") in the 1990's. However, in the following decade, the projected output fell to an average annual level of 318 mmbf. A continued imbalance of age classes was identified as a further cause for larger reductions in sawtimber output by the middle of the next century. The restricted planning horizon available to the TRAS-based model, in combination with the forecast of a potential decline in the region's production capability, were sufficient causes for developing an expanded timber projection model.

Model Selection and Development

An improved timber projection system was developed for the region using the USDA Forest Service FORPLAN model (Lord 1985). The linear programming structure of FORPLAN, compared with the TRAS model, permitted an expanded view of the region in terms of a longer projection horizon and a complete set of timber outputs. The FORPLAN model also provided a more explicit model of the dynamics of forest structure in terms of growth, inventory, and age class distribution. In addition, the forest management strategies employed by the various ownership groups could be more precisely represented in the model.

Although linear programming models in forestry have been largely directed toward optimizing management activities under somewhat singular ownership objectives, an alternative application has been proposed by Alig et al. (1984) involving the broader context of simulation. Within this perspective, a forest optimization model, rather than seeking a normative course of action, could be used to predict future outcomes based on a set of pre-defined assumptions concerning timberland management. These management strategies would be represented mathematically within the LP formulation.

The approach taken in this study simulated future timber yields from the multi-ownership Allegheny Region. General forest management strategies of the various ownership groups were identified and translated into an objective function, constraints, and silvicultural prescriptions of the FORPLAN model. Access to FORPLAN version II was made available to the Penn State School of Forest Resources by the USDA Forest Service through the Allegheny National Forest headquarters at Warren, Pennsylvania.

The general FORPLAN model is organized from several basic components: an objective function, planning horizon,

analysis areas, prescriptions, yields, activity variables, and constraints (Johnson et al. 1983). The objective function for the regional model was directed to maximizing the non-discounted harvest of sawtimber, in million cubic feet, over a 100-year planning horizon. The planning horizon was divided into 10 decades beginning in 1980 and ending in 2079. A volumetric objective was chosen over a financial objective to better represent the cumulative actions resulting from a complex of ownership decisions. These decisions are not always based on financial criteria, particularly within the public sector where volumetric measures are consistent with certain management strategies in practice; e.g., area control and nondeclining even flow. Nor can this complex of decisions be traced to any given point in time, as would be implied by a discounted cash flow analysis.

A sawtimber measure was initially used in the objective function, rather than a combined sawtimber and pulpwood measure, to reflect the primary objective of most hardwood management strategies. In part, this referenced to the traditional financial strength of sawtimber markets and the continued weakness of pulpwood prices within the region.

Acreage allocated to timber production was determined exogenously to the FORPLAN model. Implicit to the model was the assumption that the amount of timberland would remain constant over the planning horizon. The loss of timberland in this largely rural region has been minimal during the past two decades (under .1% annual) and no major land use changes are expected within the next three decades (Powell and Considine 1982).

The region's timberland was stratified among 75 potential analysis areas based on five ownership groups, three broad forest types, and five age classes. Conceptually, an analysis area represents a distinct homogeneous resource unit available to management by its owners. Ownership groups included the USDA Forest Service, the Pennsylvania Bureau of Forestry, the Pennsylvania Game Commission, private ownerships with properties over 200 acres in size, and private ownerships with properties under this size. The subdivision of private ownerships by tract size was an effort to recognize larger property ownerships having a better potential for long term management and greater likelihood of more intensive management. The forest type stratifications included the oak types, the northern hardwood types, and the allegheny hardwood type. The latter is a variant of the northern hardwoods and includes stands that typically have larger volumes and values due to higher percentages of black cherry *(Prunus serotina)*, ash (*Fraxinus* sp.), and yellow poplar *(Liriodendron tulipifera)*.

Because of a lack of more detailed age data, stand age classes were derived from stand size class information. Stand age classes were 1-30 years, 31-50 years, 51-70 years, 71-90 years, and 91 years or older and corresponded to respective stand size classes of seedling/sapling, poletimber, small sawtimber, large sawtimber, and large sawtimber exceeding a 90-year rotation age (USDA Forest Service definitions). The age assignments were derived from stand size correlations found within the 1978 Pennsylvania forest survey data (McWilliams 1985). Unfortunately, site quality information was not available in a consistent form for all ownerships and could not be used as a basis for additional stratification of the timberland base. The forest type and age class distributions within any ownership group were developed from inventory information maintained by the public agencies and, in the case of private ownership, from the USDA Forest Service plot data acquired during the 1978 forest survey of Pennsylvania.

Silvicultural prescriptions, represented in the regional FORPLAN model as a sequence of harvesting activities, described the alternative management activities that could be implemented. Timing options for each prescription described the range of ages or periods in which the treatments could be implemented; e.g., rotation or thinning ages. For each analysis area, FORPLAN generated all possible unique prescription-timing option combinations. These prescription-timing options became the linear programming decision variables, and one column was generated for each in the LP matrix. A total of 1,061 prescription-timing options were defined; an average of 16 options per analysis area.

The selection of alternative silvicultural prescriptions for the regional model was based on a previous survey of ownership groups in the Allegheny Region by Strauss and McWilliams (1987). Although this survey found certain differences in management strategies among the ownership groups, their basic prescriptions were consistent with the silvicultural guidelines developed by the USDA Forest Service for northern hardwood forests (Marquis et al. 1984).

Four prescriptions were defined, represented by three combinations of intermediate and rotation harvests for even-aged management and a selection management system for uneven-aged management. The even-aged silvicultural prescriptions were generally organized toward a rotation length of 85 to 115 years. During the rotation interval, the stands received a series of zero to two thinnings to promote growth and quality within the residual stand. Longer rotations, up to 155 years, were allowed on the analysis areas of the USDA Forest Service, Bureau of Forestry, and Game Commission because of the longer rotations that would be required under their general management strategies.

The major constraints within the model referenced to the management strategies of the various ownerships. In an effort to achieve a better balance of age classes and to sustain timber production levels on the Allegheny National Forest, the proposed management plan recommended certain production ceilings and a nondeclining even flow management policy for the Forest. An initial annual ceiling of 13.0 million cubic feet (mmcf) of sawtimber and pulpwood, as proposed, would be increased over a 50-year period until it reaches a sustainable annual level of 15.8 mmcf (USDA Forest Service 1985). To simulate these management policies, upper and lower harvest constraints were placed on the Allegheny National Forest during each decade consistent with their proposed management strategies. In addition, a nondeclining even flow constraint was used to monitor decade by decade shifts in output.

The Pennsylvania Bureau of Forestry and Pennsylvania Game Commission annually harvest approximately 1% of their even-aged forests on an area control basis as a means of establishing a normal distribution of age classes. This long term balance would be achieved by the year 2060. These agencies also manage portions of their forests on an uneven-aged basis. The Bureau of Forestry devotes 10% of its timberland to uneven-aged management; primarily as buffer areas adjacent to roads and streams. The Game Commission uses uneven-aged management on about 25% of their holdings due to a priority interest in diversifying wildlife habitats. Both agencies schedule selection harvests on uneven-aged stands on a 15-year cycle and typically remove two-thirds of the growth accruing between harvest cycles. These management policies translated into a number of constraints. On the Bureau of Forestry and Game Commission analysis areas, an upper limit constraint was set for the amount of acreage designated for even-aged management, with a second set of constraints forcing implementation of a 1% annual area control harvest on the even-aged acreage. The remaining portion of their lands was assigned to the uneven-aged prescription option.

The management strategies of the private sector were oriented to even-aged stands. Management objectives were often modified by financial and product standards, leading to a range of rotation ages of 85 to 115 years on large private tracts. Accordingly, the regional model was organized for rotation harvest of all large private properties as they entered the 80- to 110-year age classes. For large tracts, the model was allowed to make harvests at any time within this age class, subject to the further limit that, as a whole, the ownership group would harvest between 5% and 20% of its acreage in each decade. This latter constraint was believed necessary to moderate fluctuations in timber volumes marketed between decades. In order to model a relatively intensive level of management on these larger tracts, two-thirds of the large private tracts were managed with two commercial thinnings, and the remaining acreage received one thinning.

On small private tracts, it was assumed that stands were equally likely to be harvested at any time between 85 and 105 years. Accordingly, one-third of the acreage entering the 80-year age class, one-half of that reaching 90 years, and all acreage reaching 100 years were harvested to simulate this assumption. Intermediate thinnings were not allowed for the small private ownership category in order to simulate the less intensive management common to this ownership.

The timber yield coefficients for the study were based on growth and yield tables originally developed by the USDA Forestry Sciences Laboratory for the Allegheny National Forest FORPLAN model. The tables were constructed through growth simulations of inventory plot data secured from the various forest types, age classes, and site quality classes found on the Allegheny National Forest. Although the 0.5 million acre national forest is in the western portion of the Allegheny Region, the yield tables were considered to be acceptable estimates for the entire region.

Activity variables within the FORPLAN model represent the management activities (inputs) and the resulting yields (outputs). Primary activity variables were defined in the model to track acreage assigned to each prescription, sawtimber volume harvested, pulpwood volume harvested, and final harvest acreage. FORPLAN also defined internal variables to calculate timber inventory, stand average volume, and long term sustained yield capacity.

During the solution procedure, the model distributed the total acreage in each of the analysis areas among the alternative prescription-timing options. The assignments brought into solution reflected the sawtimber maximization objective function subject to the constraints imposed by the total acreage available and the complex of owner management strategies.

The model also constrained any depletion to the total forest base that might have been induced by the objective of maximizing harvested sawtimber over a finite planning horizon. Accordingly, the individual ownerships were required to carry a timber inventory volume during the last decade that at least equalled the average inventories carried during all previous decades under their management strategies. This constraint assumed that the ownerships would not intentionally deplete their growing stock, at least in aggregate. For the public ownerships, this assumption was supported by their sustained yield management attitudes. Although this assumption may be less supportable for the private sector, there has been no evidence of any private forest depletion within Pennsylvania (Powell and Considine 1982).

Results

A major increase in available sawtimber was forecast for the Allegheny Region over the 100-year period (table 1, fig. 2). Starting from a level of 280 million cubic feet (mmcf) in decade 1, the model projected near continual increases in sawtimber availability throughout the next six decades, reaching a peak volume of more than 950 mmcf in both decades 6 and 7. A modest decline was registered in the eighth decade to 880 mmcf, followed by an additional drop of 27% to the 640 mmcf level in the final two decades. Estimated sawtimber production in decades 6 and 7 were more than triple the level forecast in decade 1.

The source of sawtimber by ownership groups was in direct proportion to the amount of land controlled by each group; with 61% of the total coming from private forests, 24% from state properties, and 15% from federal lands (table 1, fig. 2). A minor shift in the private to public ratio was noted over the study period, with the first three decades having a 62:38 ratio and the last three decades a 58:42 ratio. The increased proportion of public timber during the latter decades reflected the even flow management strategies on public lands, coupled with a decline in timber availability from private lands.

Although the contributions from each forest type varied from decade to decade, overall the allegheny hardwood type was the most productive, accounting for 33% of the sawtimber while

Table 1.--Projected sawtimber harvests from the Allegheny Region by decade and ownership group, 1980-2079.

Ownership:	Allegheny National Forest	Pa. Bureau of Forestry	Pa. Game Comm.	Private small tract	Private large tract	Total
Decade			Volume (*mmcf*)			
Size *(1000 acres)*:	433.6	489.4	215.0	1,068.5	683.1	2,889.6
1	46.8	62.8	17.1	52.5	101.2	280.4
2	89.4	58.9	24.0	77.6	202.6	452.5
3	99.4	79.0	52.6	225.8	184.5	641.3
4	98.4	115.5	57.6	141.2	166.6	579.3
5	105.7	111.8	53.3	261.9	226.8	759.5
6	118.4	118.4	46.2	188.0	492.8	963.8
7	126.3	153.8	80.5	176.5	414.6	951.7
8	129.2	123.4	49.2	29.7	548.6	880.1
9	112.8	152.8	74.1	163.5	132.3	635.5
10	109.2	129.3	42.2	36.4	341.7	658.8
Total swtmbr.	1035.6	1105.7	496.8	1353.1	2811.7	6802.9
Swtmbr. from thin./sel.	97.1	223.7	191.7	0.0	472.8	985.3
Total pulpwd.	544.8	982.6	418.6	1110.8	2178.5	5235.3
Pulp from thin./sel.	146.6	503.6	256.6	0.0	1088.9	1995.7

representing 28% of the timberland. Oak type forests produced 21% of the sawtimber and represented 22% of the timberland. The remaining 46% of sawtimber originated from the 50% of timberland typed as northern hardwoods.

Over the 100-year period, 85% of the available sawtimber would be provided from rotation harvests, with the remainder coming from thinnings and selection harvests (table 1, fig. 3). The proportion of sawtimber coming from rotation harvests increased over the study period, with 59% developed from rotation harvests in decade 1, 75% in the next two decades, and 89% in the final seven decades. The estimated yield per acre for rotation harvests also increased over the study period, averaging 1.3 thousand cubic feet/acre (mcf/a) in the first three decades,

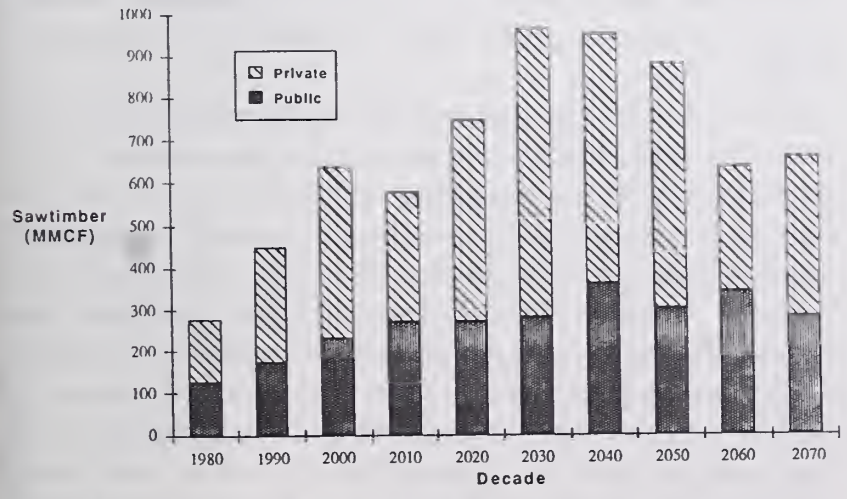


Figure 2.--Projected sawtimber availability by ownership, the Allegheny Region.

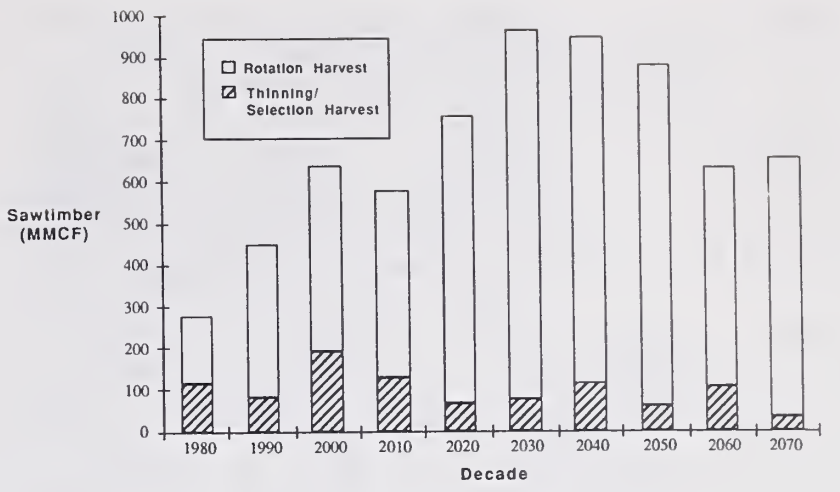


Figure 3.--Projected sawtimber availability by harvest type, the Allegheny Region.

2.1 mcf/a in the next three decades, and 2.2 mcf/a in the final four decades.

A total of 5.2 billion cubic feet of pulpwood was available for harvest during the 100-year period (table 1). The distribution of the pulpwood output by ownership groups was also in proportion to the size of the ownerships. As might be anticipated, a substantial percentage of the total pulpwood (38%) originated from intermediate thinnings and selection harvests. However, the gradual advance in the average age structure of the forest, and the associated reduction in the opportunities for commercial thinnings, resulted in a moderate decline of pulpwood availability over the study period.

Within the private ownership group, a cyclical pattern was evident in their proposed harvest of sawtimber. This was attributed to the initial imbalance in age classes held by these ownerships, in combination with their management strategy of releasing all timber to the market as it reached rotation age. A gradual increase in private sawtimber harvests was evident over the first six decades as the initial acreages of large sawtimber were harvested, followed by even larger initial acreages of small sawtimber and poletimber (table 2). However, a considerable drop in output was forecast in decades 8 and 9 as the relatively small initial acreage of seedling/sapling class material reached maturity.

The organization of public forest management strategies toward sustained production resulted in a uniform increase of public sawtimber throughout the study period. On the state properties, the increased output was attributed to the effects of the area control strategy, which resulted in a backlog of old growth stands (> 110 years). A certain fluctuation in total sawtimber output was evident, largely attributed to the variations in commercial thinning operations. On the National Forest, the nondeclining even flow constraint held output to a range of 130-158 mmcf per decade. By the fourth decade, the forest was capable of maintaining its upper limit of production through rotation harvests, which eliminated the need for commercial thinning operations. Longer rotation lengths were evident on public ownerships during decades 7 through 10, with the

Table 2.-- Age class distributions, before rotation harvest, for private and public timberland in the Allegheny Region by selected decades.

Age class		Decade 1 (year 1980)		Decade 6 (year 2030)		Decade 11 (year 2080)	
		% of timberland acreage					
1-30 yr.	Public	2.7		27.1		27.6	
	Private	7.3		29.8		35.2	
	Total		5.5		28.3		31.5
31-50 yr.	Public	24.8		13.7		15.1	
	Private	37.1		18.7		27.5	
	Total		32.3		16.9		26.9
51-70 yr.	Public	46.1		3.0		18.7	
	Private	29.8		7.0		20.2	
	Total		36.2		5.5		19.4
71-90 yr.	Public	24.2		19.8		15.9	
	Private	25.8		32.1		14.2	
	Total		25.2		29.2		14.8
91-110 yr.	Public	2.3		23.4		3.2	
	Private	0.0		12.4		2.8	
	Total		0.9		15.0		3.1
>111 yr.	Public			13.0		19.5	
	Private			0.0		0.0	
	Total				5.1		4.3

average stand age of harvested material ranging from 140-150 years.

The cumulative effect of the proposed forest growth and harvest patterns over the study period was a more balanced distribution of age classes within the aggregate forest (table 2, fig. 4). Initially, nearly 95% of the timberland was in poletimber and sawtimber size class material. By the midpoint of the study, approximately 45% of the timberland was harvested and reestablished in seedling/sapling and poletimber sized stands. The more restrictive harvesting programs on public lands resulted in about 15% of these forests extending to age classes over 90 years in age. The primary imbalance in the middle period was in the 51- to 70-year class stands (small sawtimber) that originated from the initial shortages of acreage in the 1- to 30-year class (seedling/sapling).

Over the 100-year period, an estimated 3.0 million acres of timberland was scheduled for rotation harvest. Considering that 2.8 million acres was organized under even-aged management, the first cutting cycle for this complex was completed by the tenth decade. Assuming an average rotation of 100 years, the projected schedule was consistent with a sustainable acreage harvest of 10% per decade. At the conclusion of the study, an improved balance was evident among the four basic stand size classes, with 32% in seedling/sapling, 27% in poletimber, and 41% in sawtimber stands. This general balance was found on both public and private forests.

Commercial thinnings and selection harvests were imposed on 3.5 million acres of timberland during the study period.

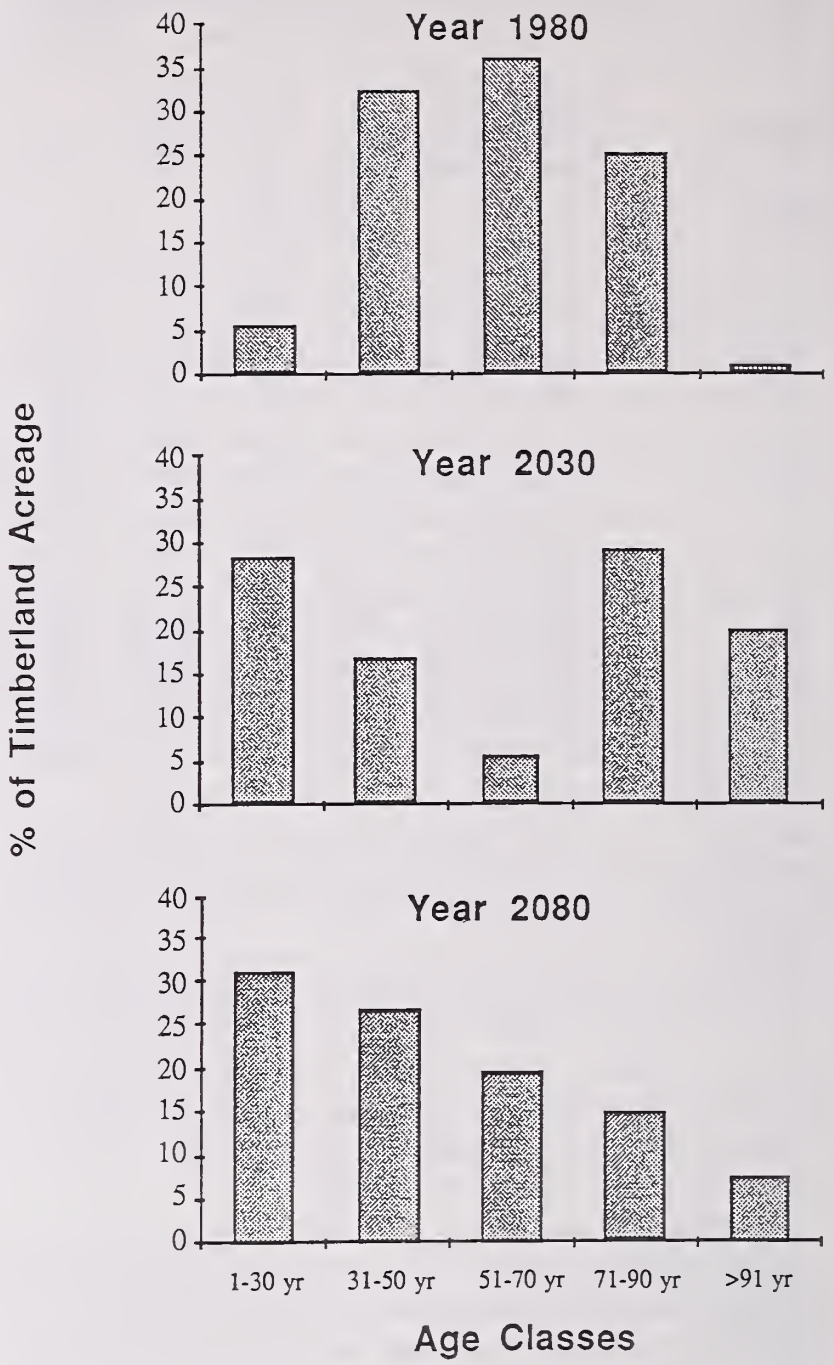


Figure 4.--Current and projected age class distributions from Allegheny Region timberland.

Nearly 65% of this activity was scheduled during the first four decades when large portions of timberland were in the poletimber and small sawtimber classes. As previously noted, none of the small tract private ownerships were scheduled for commercial thinnings.

Inventory, harvest and growth data from the FORPLAN model provided additional insights on the proposed structure of the Allegheny Region timberland (table 3). Between the first two decades, inventory increased by 7% as growth exceeded the region's harvest by a ratio of 1.35:1. From decades 2 to 6, inventory remained fairly constant, with harvests slightly exceeding growth. As harvesting accelerated and growth declined during decades 6 through 9, inventory was reduced. After the ninth decade, harvests declined and growth accelerated, as a major portion of the forest entered faster-growing age classes. At the conclusion of the study period, the regional inventory was recovering from the accelerated cutting of the middle periods.

Table 3.--Inventory, growth and harvest volumes (in mmcf) from the Allegheny Region FORPLAN model.

Period	Inventory	Harvest	Growth
1	4957.8	953.2	1290.5
2	5295.1	1104.6	1127.8
3	5318.3	1277.1	1318.8
4	5360.0	1117.8	1047.1
5	5289.3	1246.5	1152.2
6	5195.0	1473.1	945.7
7	4667.6	1399.8	1079.7
8	4347.5	1322.9	922.8
9	3847.9	1039.0	1259.5
10	4168.4	1104.7	
Average	4854.7	1203.8	1127.1

Overall, harvesting slightly exceeded growth in the region. The growth-to-drain ratio over the study period was .94:1. However, there was no indication that the projected level of harvest would deplete the regional timbershed over the long run. Based on FORPLAN estimates, the regional long-term sustained yield capacity was 1,222 mmcf per decade, which was slightly above the scheduled average harvest of 1,204 mmcf. In addition, the projected average inventory of 4,855 mmcf per decade for the region was higher than the long run stand average volume of 4,016 mmcf. Stand average volume represented the average inventory that would result from managing the forest indefinitely under the prescribed management regimes.

Discussion

A unique aspect of this study was the use of the FORPLAN linear programming system as a regional simulation model. Since FORPLAN is normally used on single ownership forests in the context of an optimization model, some comment is appropriate on its suitability for multi-ownership resource settings. Several advantages were evident.

FORPLAN is a comprehensive model, capable of simultaneously modeling the four inter-related components of an aggregate timber supply analysis outlined by Alig et al. (1984): (1) land allocation, (2) the progression of the timber inventory under the dynamics of growth and mortality, (3) harvest flows, and (4) timber inventory and management strategies.

The linear programming structure of FORPLAN permitted an explicit representation of management strategies for each ownership, including complex and inter-related long-term strategies (e.g., even-flow policies). The model also forced a careful examination of all assumptions. Regional timber supply models, by their nature, are heavily dependent on their assumptions. FORPLAN required an explicit description of these assumptions. Although it was difficult to develop management strategies for certain ownership groups, the problem is inherent to regional modeling and is not unique to FORPLAN.

The major disadvantage of FORPLAN was the necessity of specifying a single objective function for multi-ownerships (Alig et al. 1984). However, it should be noted that as the model becomes more heavily constrained by the complex of management strategies placed on each ownership, the model had less choice in achieving an "optimal" solution. Hence, the model becomes more simulation and less optimization, with the choice of the objective function less critical.

Some assessment of this study's predictions can be made from certain projections of the national hardwood markets and from other resource evaluations of the Allegheny Region. At the national level, the USDA Forest Service forecasts a tripling of hardwood products demand over the period 1980-2030 and a doubling of the hardwood sawtimber supply, leading to a predicted increase in the real prices for certain hardwood products (USDA Forest Service 1982). The primary constraints upon supply were the physical limits of the resource and a possible reluctance among private ownerships to market their timber. Overall, the national demand for hardwood products during the next 30 to 40 years should function as a complement to the region's output capability.

Previous forest surveys of Pennsylvania have shown a gradual increase in sawtimber harvests from the Allegheny Region over the past three decades (Bones and Sherwood 1979, Ferguson 1958, Ferguson 1968). A 20% increase in harvests occurred between the 1950's and the 1970's, with the initial 10-year consumptive level of 206 mmcf of sawtimber increasing to 252 mmcf by the 1970's. The industrial base study of the region's forest products industry also showed an annual sawtimber consumption of 26 mmcf in 1981, excluding log shipments to areas outside the region (Westman et al. 1985).

A positive trend in pulpwood removals has been evident in the Allegheny Region (USDA Forest Service series). Between the 1960's and 1970's, pulpwood harvests doubled, increasing from 76 mmcf per decade to 152 mmcf. Furthermore, the initial 3 years removal rate in the 1980's was 70% higher than for the same period in the 1970's (Widman 1983).

The TRAS model of the region's forest system (Strauss and McWilliams 1987) showed a potential doubling of output from the 1970's harvest rate to the 1980's availability level of 657 mmcf. A further expansion of 1.5% was estimated for the 1990's, followed by a 24% decline in the third decade (fig. 5). Over the 30-year study period, a total of 1,833 mmcf of sawtimber was identified as available, whereas the FORPLAN model predicted a total of 1,374 mmcf for the same period.

The 33% difference between the two studies was largely attributed to the alternate structure of the two models and, to a lesser extent, the alternate sources of growth and yield information used in the two models. In comparing the two models, the TRAS model had a more pragmatic format, with the forest stands moved forward in time under linear growth estimates and, upon reaching a particular dimension, automatically scheduled for harvest or intermediate thinnings. A greater flexibility was provided by the linear programming design of the FORPLAN model. Here, the optimal solution for the problem was deter-

mined through the interplay of the model's curvilinear yield tables and the selection of harvesting and thinning schedules from an array of time periods, ownership groups, and forest types. Central to this selection process was the need for maximizing sawtimber volume over the planning horizon. In addition, the model had the general choice of selecting lower levels of output during initial periods versus increased volumes from subsequent periods. In contrast, the harvests suggested by the TRAS model, though technically correct, were applied in a more pragmatic fashion, with the process largely guided by forest management strategies applied within a short-term perspective.

Both of these studies were limited in their ability to identify the quality of the proposed timber. Three general qualitative subdivisions were evident in: (1) sawtimber originating from rotation harvests, (2) sawtimber from intermediate harvests, and (3) pulpwood. The FORPLAN study anticipated that 14% of the total sawtimber volume would originate from thinnings and selection harvests, with 40% of this material developed during the first three decades. However, the sawtimber from thinnings is not as desirable as sawtimber from rotation harvests due to the former's higher cost and lower quality. Both studies found that the yield per acre from thinnings would average only 20% of the yield from rotation harvests. In addition, the TRAS model showed 60% or more of the volume in thinnings would be in tree diameters 14 inches or less, whereas rotation harvests had under 40% of its volume in this lower diameter range.

A comparison of the sawtimber forecasts from the two models with the previous trend in timber harvests (fig. 5) suggests that the future trend in output may lie somewhere between the bounds of the two studies. Essentially a greater volume of rotation harvests could be made available than originally forecast by the FORPLAN model and a lower volume of intermediate harvests would be scheduled, as forecast by the TRAS model. This compromise would also represent a logical progression in sawtimber output to the higher levels forecast by the middle of the next century.

One of the key impediments to the success of the proposed forest management strategies will be marketing the major volumes of pulpwood from this forest. As projected, an average of 523 mmcf of pulpwood will be available each decade, with the trend in availability showing a gradual decline over the study period. The current trend in pulpwood consumption suggests a potential consumption of 230-260 mmcf during the 1980's, slightly more than one-third of the region's available harvest. Clearly, an expansion in the market outlets for pulpwood will be a prerequisite to the complete implementation of the region's forest management strategies.

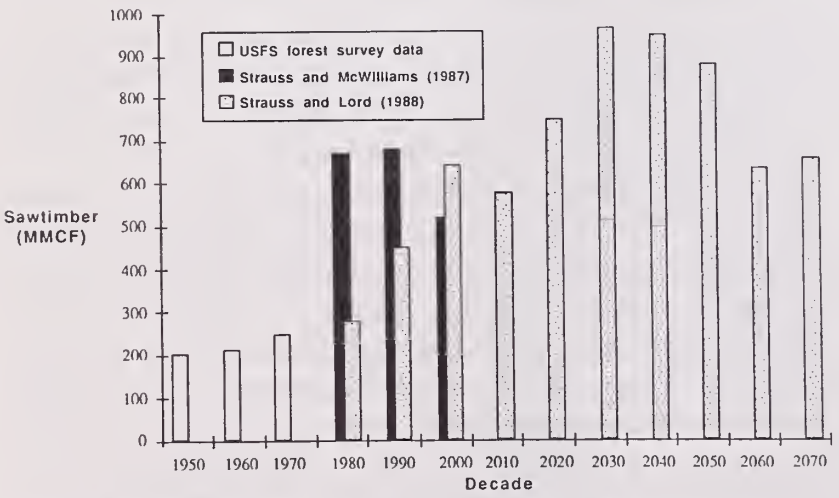


Figure 5.--Historic and projected sawtimber harvests for the Allegheny Region.

Timber that is not harvested on the basis of either reluctant ownerships or unavailable markets will simply accumulate as additional inventory. In turn, added stocking will only serve to reduce the aggregate growth and quality conditions of the existing forest and lengthen the eventual rotation of mature stands. Any extension of rotations will delay the achievement of a more desirable age class balance.

Conclusions

FORPLAN proved to be an effective simulation tool in this aggregate timber supply analysis. It was flexible, relatively easy to use, and allowed for the explicit representation of a fairly complex set of assumptions. Major shortcomings included a difficulty in specifying an ideal objective function and dependence on a mainframe computer. There appears to be potential for making an expanded use of FORPLAN in modeling other multi-ownership forest regions.

Although various arguments can be made about the timing and magnitude of the predictions presented by the model, certain characteristics of the forest system support the general conclusions of this study. First, the magnitude and quality of timber resource within this region have been confirmed through a continuing series of forest surveys and updates. Second, the biologic character of this resource can not be denied, and support the increase in timber available for harvests. Furthermore, the incremental growth process has been modeled and shown to be consistent with the predicted advance of stands through their successive age classes and the eventual attainment of merchantability at prescribed rotation ages.

The most debatable aspect of the model is its capacity to accurately predict the actual volumes of timber that will be either released to or accepted by the markets. The model reflects an optimal scenario largely based on the management desires of the forestry profession. Although this advice is closely considered on public forests it may not be consistent with the future decisions of the private sector, nor with economic realities of timber markets.

A major expansion is expected in sawtimber production for the Allegheny Region. This note of optimism is supported by the increased world demand for hardwood timber resources and by this region's ability to provide a quantity and quality of timber unlike any other timbershed. In all likelihood the private sector will respond to this demand with an accelerated cut. Whether the forests will be capable of regenerating similar timber types is currently under debate. However, strong markets and premium prices for timber should provide the necessary incentive for reinvesting in this resource base.

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Modeling Regional Timber Supply in California

Bruce Krumland and William McKillop

Abstract.--The California Timber Supply (CATS) model was used to obtain projections of future potential timber harvests, growth, and inventories for private lands in California. CATS consists of an integrated system of computer modules that provides for inventory processing, data management, growth and yield simulation, linear programming solutions, and post-LP analysis.

The California Department of Forestry and Fire Protection is required by law to conduct periodic assessments of the State of California's forest and range resources under FRRAP (Forest and Rangeland Resource Assessment Program). Since 1979, funding has been provided to the University of California, Berkeley, with the objective of obtaining projections of potential future timber inventory and harvest from private lands in California on a decade-by-decade basis.

Three alternative models were considered for projecting timber inventory and harvest in California. Consideration was given to adapting the RMS 80 model of New Zealand Forest Products Ltd. (McLean 1981). Further work on this model was terminated because it was essentially an even-aged model and was tied to the concept of an "Equivalent normal forest." Consideration was also given to the TREES model which had been developed for the Timber for Oregon's Tomorrow Project (Beuter et al. 1976, Tedder et al. 1980). The Oregon Department of Forestry's IBM conversion of this model was adapted to the IBM 3090 at UC Berkeley and preliminary analyses were made (Oregon State Department of Forestry 1980). Use of the model was not pursued because a more powerful method of modeling the growth and yield of uneven-aged stands was needed. In addition, the construction of input files for TREES proved to be time-consuming and the model required comprehensive yield tables by species group for even-aged stands. Such yield tables were not readily available for California forests. It was finally decided that a new comprehensive timber supply model was required and that its growth and yield component should be based on the CRYPTOS/CACTOS type of models developed at UC Berkeley by Krumland and Wensel (Krumland 1976, Wensel and Daugherty 1985).

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An Overview of CATS

CATS has been designed to provide an integrated system for producing timber supply projections from regional timber inventory data. At its core are two main modules: CATSYG which performs individual stand growth and yield projections and CATSLP which builds, solves and reports on LP models. CATSLP can optionally prepare the solution basis for more detailed post-processing by CATSYG.

CATSYG

This module is a central process server that is programmed by information contained in a control file. Control information is used to set up job parameters, set data base selection criteria, control output disposition, and indicate the runtype to be performed. While CATSYG is capable of performing several operations, the two major ones used in this study are:

Calibration.--A main component of this module is a growth projection system comparable in function to the CRYPTOS/CACTOS models. In calibration runs CATSYG uses all the available data in a timber inventory to compare actual with predicted values of this system. It "suggests" calibration factors as well as producing data files that can be used in directly refitting any component equation.

Option processing.--In this runtype, each inventory unit (plot or stand data) is subjected to any number of management options. In this context, an option is described by a series of "growth simulation language" (GSL) statements. Highlights of the CATS GSL are:

- ✦ program control structures common to formal programming languages: if/then/else/endif, loops, branching, callable sub-procedures;

- ✦ math/assignment statements;
- ✦ built in macros that provide for growing the stand, flexible harvest control, sprouting/ingrowth functions, determining "point counts," and indexing;
- ✦ "read only variables" that give access to all the stand "header" information as well as every major stand/species/size class characteristic at any time during a simulation. Additional GSL statements allow users to program the values returned by these variables.

The CATS GSL was designed to provide flexibility to produce any type of yield forecast without being hampered by built-in software limitations. This innovative development will be described in more detail in a forthcoming paper.

CATSLP

This module takes special yield files produced by CATSYG, creates LP tableaus, solves the LP, and produces tabular and graphic reports. Initially, this module creates a programmable accounting tableau of major variables of interest. The implementation used the usual "stand acreage" constraints and growth, harvests, and standing inventory volumes cross-classified by owner and species group (conifer or hardwoods). Run-specific constraints and objectives are introduced by operations on the accounting tableau variables.

IMPLEMENTING CATS FOR CALIFORNIA

CATS was designed to produce regional timber supply projections for California. In its present form it is set up to deal with the USDA Forest Service "Forest inventory and analysis" data (Bolsinger 1986), commonly referred to as the "Forest Survey" data. It could, however, be adapted to process inventory data for individual private properties or tracts of public land. Information on the most recent USDA Forest Surveys are reported by Colclasure et al. (1986a, 1986b), Hiserote et al. (1986), and Lloyd et al. (1986a, 1986b).

Forest Survey data for California cover more than 1,200 sample points each of which consists of five sample plots. Consideration was given to combining sample points into more or less homogeneous stand types, but it was decided that this combining would introduce an element of inaccuracy and lack of realism. Accordingly, each sample point was treated as an individual stand in the CATS model. The forest survey data were used by CATSYG to calibrate the growth simulation component.

Northern California Regions

Each sample point is identified by the county in which it is located. Ideally, an analysis such as this might be carried out on a county by county basis, but lack of data required that the sample points be aggregated into five regions in northern California. These are:

1. The North Coast region consisting of Del Norte, Humbolt, Mendocino, and Sonoma counties.
2. The Northern Interior region consisting of Siskiyou, Modoc, Trinity, Shasta, and Lassen counties.
3. The Sacramento region consisting of counties south from Tehama and Plumas to Sacramento and El Dorado.
4. The San Joaquin region consisting of counties from San Joaquin, Amador, and Alpine south to Kern, Tulare, and Fresno counties.
5. The Central Coast region consisting of counties from Marin and Solano south to San Benito and Monterey.

Southern California is listed by the USDA Forest Service as a survey region, but the number of sample plots in southern California counties are too few to permit analysis.

Forest Ownerships

The "Forest Survey" data cover only private ownerships and non-U.S. Forest Service public land in California. At the present time, the CATS model is set up to process data for private land but could be adapted to forest inventories for individual National Forests or groups of National Forests. Two classes of private ownership are recognized in the CATS model: (1) industrial forest land, and (2) nonindustrial private ownerships. Nonindustrial ownerships under 50 acres in size were excluded from the timber-producing land base.

The number of acres by ownership and region that each sample point represents was provided by the FRRAP staff of the California Department of Forestry and Fire Protection.

Forest Management Practices

A survey of industrial and non-industrial forest management practices was conducted to provide a realistic basis for the specification of management options.

The current version of the model uses nine types of basic management options for each decade in the 1985-2055 period of analysis. The nine options are:

A. Do nothing (no harvests, just let the stand grow).

B. Special zones. Cut half the merchantable volume over 16 inches dbh, ensuring that the remaining stand meets the legal minimum stocking standards. Stands must have at least 5,000 board feet to the acre to be considered for harvesting.

C. Poor sites. Do an "economic" clearcut; regenerate to meet legal minimum stocking standards. Repeat clearcutting and regeneration whenever standing volume exceeds 5,000 board feet per acre.

D. Well-stocked even-aged young growth conifer stands with at least 80 percent of the stand volume in trees of 11 inches dbh or greater. Clearcut and regenerate with 400 conifers per acre.

E. Commercial thinning of well-stocked young growth conifer stands with a clearcut final harvest 20 years later and restocking with 400 conifers per acre.

F. Well-stocked uneven-aged young growth conifers. Partial cutting to maintain current stocking and dbh distribution.

G. Non-industrial private stands not described above. Remove one-third of the standing volume in trees 16 inches dbh and greater, provided the conifer harvest volume is greater than 3,000 board feet per acre. Meet minimal stocking standards following harvest.

H. Industry old-growth stands or marginally stocked conifer stands or predominantly hardwood (merchantable) stands on good sites. Clearcut and regenerate with 400 conifers per acre.

I. Industry stands not described above. If stocked with conifers, attempt to convert the stand to a viable unevenaged structure. If this is not feasible, clearcut and regenerate.

J. Industry non-stocked lands or predominantly unmerchantable hardwood stands on better sites. Provisions were made to clearcut and regenerate all of these stands in the first 3 decades.

It should be noted that all options were coded so that all post-harvest regeneration practices were designed to leave stands with legally acceptable stocking.

The application of a particular option to a specific stand may occur during any of the seven decades in the projection period. Thus if the timing of each management practice is considered as well as the type of practice, there are numerous options to draw from in selecting the prescription that is appropriate for a given stand type, but irrelevant options were, however, eliminated on the basis of experience.

It should be noted that in current runs of models, hardwood competition is eliminated from industrial clearcut lands. Industry representatives indicated that brush and hardwood control would normally be practiced in regenerated stands. It should also be noted that utilization standards were imposed on harvest practices with the minimum tree dbh tallied in final (clearcut) harvests set at 16 inches in the first decade and declining to 9 inches in the fourth decade.

CATSLP Implementation

The CATSLP module was set up to treat decadal regional growth, harvests, and inventory volumes cross-classified by owner (industrial, non-industrial) and species group (conifers, hardwoods) as primary accounting variables. The relative "weights" given to hardwoods in the objective functions was 30% of conifer values.

Current runs of the model were designed to maximize volume or basal area harvest subject to constraints on the terminal inventory and numerous flow requirements. The use of linear programming makes it comparatively easy to expand the model to a financial optimizing system.

The linear programming structure also makes it easy to examine the implications of different types of constraints with respect to such things as changes in harvest level from period to period or the acreage of a particular timber type that can be subject to a given harvest/silvicultural regime.

Projections of Inventory, Harvest, and Growth

Projections of timber inventory, average annual potential harvest, and average annual growth were developed by region and ownership for seven decades: 1985-1995, 1995-2005, 2005-2015, 2015-2025, 2025-2035, 2035-2045, and 2045-2055 and compared with estimates for the 5-year base period 1980-85. Each period runs from the middle of the first year to the middle of the last year in the period.

Timber inventory estimates are for the middle of each period. Annual growth includes ingrowth into the diameter classes represented in the standing volume estimates as well as increment in that standing volume. Harvest levels for the 1980-1985 base period were generated by the model under the constraint that conifer harvests had to be equal to the estimate of the average 1975-85 levels provided by the State Board of Equalization. (The 1975-85 period encompasses the peaks and troughs of the lumber market in recent years.)

Accurate estimates were not available for hardwood levels, so the 1980-85 hardwood cut was constrained to be no more than 15 percent of the conifer cut.

Several types of basic computer runs were made for each region to span the types of aggregate management strategies likely to prevail in different regions and ownerships. Runs TB2, TC2, TB4, TC4, TB7, and TB7 were used for the North Coast, Northern Interior, Sacramento, and San Joaquin regions. The total private conifer harvest (from industrial and non-industrial lands combined) was maximized over the first two decades (1985-2005) in TB2 (board feet) and TC2 (cubic feet), over the first four decades (1985-2025) in runs TB4 and TC4, and over all seven decades in runs TB7 and TC7. These runs were subject to constraints that (1) the conifer standing volume in the final decade (2045-2055) could not be less than 80 percent of the 1980-85 level, (2) the average annual conifer cut on industry lands in 1985-2005 could not be less than 80 percent of its 1980-

85 level, and (3) the hardwood harvest in all forecast periods from 1985-1995 onwards could not exceed 25 percent of the conifer cut. Also, it was required that conifer cuts be equal in each decade over the maximization period to facilitate comparisons between different runs. Runs were also made which maximized the conifer cut from industrial lands alone.

The current level of conifer growth in the Central Coast region is significantly greater than the harvest level; so, it would have been unrealistic to use the normal formulation of the model for that region. M7 was used along with a variation of it, M8. Run M7 maximized the sum of the conifer cuts (in square feet of basal area) over the seven decades plus the final inventory (in terms of basal area) in 2045-2055 subject to the constraint that the average annual conifer cut could not be less than the 1978-85 level. In run M7, the harvest level had to be the same for all decades in the maximization period. In run M8 it was permitted to vary by plus or minus 25 percent from decade to decade.

Although it would have been possible to make many more alternative runs of the model, budgetary limitations made it necessary to limit its use to the runs described above. In the judgment of the investigators, those runs (with their associated constraints) are the most useful scenarios that could be constructed within the limits of the research budget. Runs TB7 and TC7 respond to the often-heard query: "Can current levels of private conifer timber harvest in California be maintained?" Runs TB2 and TC2 reveal the maximum levels of conifer harvest that appear to be possible over the next two decades. Runs TB4 and TC4 are intermediate between the two, and in the opinion of the investigators give a more likely indication of potential future timber harvests, inventories, and growth.

Overview of Harvest Projections

The level of private timber harvest in California has undergone a secular decline since the mid-fifties when it was approximately 5 billion board feet per year. In 1982 it reached the lowest level on record of 1.5 billion. The results of various runs indicate that this downward trend has been arrested and that future standing timber volumes will permit an average cut level of over 2 billion board feet per year for the foreseeable future.

There will, however, be a significant change in the type and location of timber harvests in the future. In general, logging of old-growth from non-industrial lands preceded harvest from lands owned by the forest industry so that non-industrial young growth is at a more advanced stage than forest industry young growth. Thus, as forest industry harvests its remaining old-growth timber and larger young-growth, it will turn increasingly to non-industrial young growth stands as a source of supply. The transition from an old-growth timber resource to a young growth one has been underway for the last two decades on private lands in California and will continue for the next decade or so. This will lead to substantial changes in wood processing technology but the impact on regional forest economies will be mitigated, provided planned harvest levels of old-growth timber from National Forests are achieved.

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Implementing an Ownership-Behavior Simulation of Private Sector Timber Supplies

Robin Marose, Raul Tuazon, and Lawrence S. Davis[1]

Abstract.--This paper discusses the applicability of optimization, general equilibrium, and simulation models for statewide assessment and policy analysis, and describes in detail the simulation system developed by the Forest and Rangelands Resource Assessment Program. The system's capabilities are demonstrated for two different scenarios that affect future timber supply from private lands in the North Coast Region of California.

The Forest and Rangelands Resource Assessment Program (FRRAP) is legislatively mandated to periodically assess the status of California's public and private forest and rangelands, and to identify emerging trends that are likely to affect future condition and use. The FRRAP Information and Analysis System (fig. 1), including the CALPLAN simulation model (Davis et al. 1987), has been developed to meet this mandate. The System projects future conditions under a variety of assumptions to meet the objectives of the assessment or analyze legislation and other state policy options that address current or emerging issues.

This paper briefly discusses the applicability of optimization, general equilibrium, and simulation models for statewide assessment and policy analysis. An overview is provided of the FRRAP simulation approach, which uses behavior classes to represent variation within ownership groups. A more detailed discussion of the System is provided in the 1987 FRRAP Assessment (California Department of Forestry and Fire Protection 1988). The System's capabilities are demonstrated for a continuation of current trends scenario, as described in the Assessment, and an alternative scenario that affects future timber supply and wildlife habitat on nonindustrial forestland in the North Coast Region of California.

FRRAP ANALYTICAL MODELING REQUIREMENTS

The development of the FRRAP analytical system was based on the following criteria:

1. State-wide applicability for both forest and rangelands, while maintaining county level resolution.
2. Consideration of the environmental consequences, as well as the benefits of commodity production from land management activities.
3. Adequate representation of the unique characteristics of the multiple public and private ownerships present in the state, as well as the variation that exists within each ownership.
4. Flexibility and applicability to the wide range of issues and options pertinent to forest policy in California at the state level or for any distinct region of the state.
5. Utilization of an intuitively satisfying methodology with explicit assumptions to aid in communicating with county governments, interest groups, or other parties.
6. Utilization of the best available existing data sources, and have the capability to integrate the results of current and future research.

CHOICE OF MODEL

A variety of different approaches and models are available for assessment and policy analysis. Based on the stated criteria, optimization, general equilibrium, and simulation approaches were evaluated to determine the best approach to meet the FRRAP mandate.

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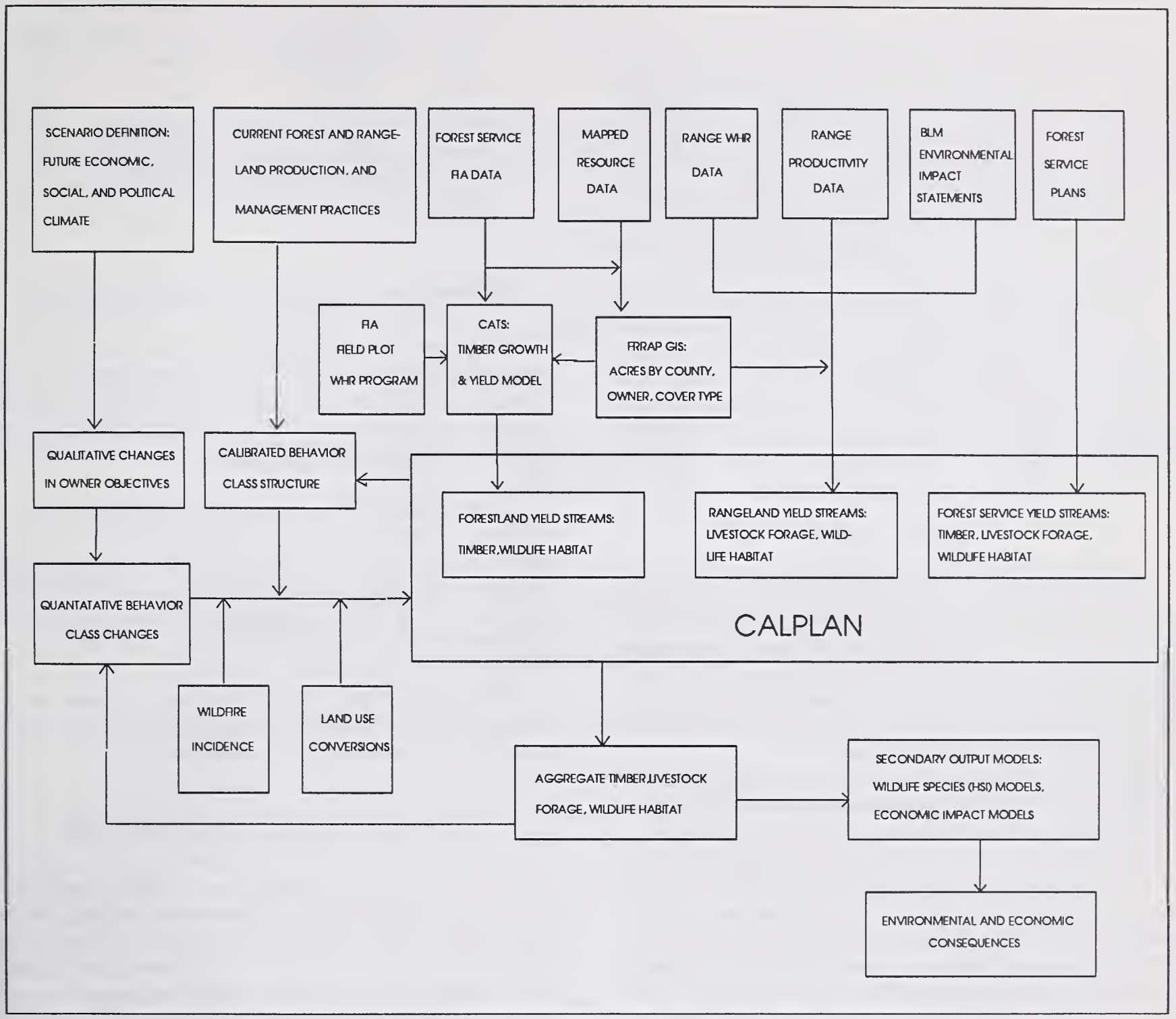


Figure 1.--The FRRAP information and analysis system. Source: California Department of Forestry and Fire Protection, 1988.

Optimization Models

Commonly used optimization approaches such as linear programming have land management and resource production activities driven by an objective function that maximizes financial returns or commodity production or minimizes cost, for example. This may be appropriate for a single landowner with well defined objectives and constraints, but becomes more problematic when applied to California, with a wide diversity of owners. Even for a single owner such as a national forest, experience has shown that attempts to produce a realistic model formulation can lead to large, costly, complex models that are often not understood or trusted by outside parties.

Deriving a realistic objective function for California is impossible now, given the importance of recreation, wildlife habitat, sub-division for housing, and agriculture, as well as timber production as viable land use options. Also, people may own land for aesthetic reasons, making forecasts based on maximizing returns from commodity production inappropriate.

In addition, the complex pattern of social and political pressures in the state imposes constraints on viable management practices. These pressures affect management in a unique fashion for different counties and ownerships, and will continue to evolve over time. Even if the constraint set representing these pressures could be somehow quantified, the model would be too large, costly, and complex to meet the requirements of FRRAP.

General Equilibrium Models

General equilibrium models are another class of models used in forest assessment and policy analysis. These models usually focus on prices and output levels of various resource commodities under different market conditions. General equilibrium models are econometrically derived, based on a set of interrelated equations that describe the underlying structure of the market. The main advantage of these models is the ability to incorporate and demonstrate market feedback affects due to changing output levels, through the structural equations.

The FRRAP modeling requirements limit the applicability of general equilibrium models, however. Production cost and demand data are not available at the county level. Non-priced outputs and other factors dominate the changing pattern of land use and ownership in California. It is also difficult to explicitly recognize multiple land ownership and use patterns within the context of general equilibrium models.

Simulation Models

Simulation models are commonly used in forestry applications for projecting timber yield, wildlife habitat, and environmental impacts such as sedimentation that result from management practices. Common applications of simulation include generating yield streams required for use in optimization models, or portraying the trade-offs of alternative management options available to a small landowner.

Application of simulation at the state level is difficult given that aggregation of owners is necessary for a workable system. Representing individual owners in the model would be an impossible task, while simulating typical management regimes of a few ownership groups would be too simplistic. The simulation approach used by FRRAP, however, uses an innovative concept of behavior classes to sub-divide broad ownerships into functional groups based on unique objectives, constraints, management practices, and yields.

Advantages of the FRRAP Simulation Approach

Relative to other approaches, the main advantages of the FRRAP simulation approach include:

1. Direct representation of the variation within broad ownership groups (criterion #3).
2. The simulation model itself relies on a relatively simple methodology that can be communicated to outside parties (criterion #5).
3. Scenario simulation, described in subsequent sections, involves translating broad assumptions about future social, political, and economic conditions into changes in owner behavior based on historical trends and expert opinion. Since the process is performed outside the model, the critical decisions in generating a scenario can be made explicit and easily communicated to outside parties (criterion #5).
4. Expert assessments of future demographics, economic conditions, politics, legislation, federal and state policy can be used to generate alternative future scenarios (criterion #6).

Disadvantages of the FRRAP Simulation Approach

Relative to other approaches, the process of translating the broad assumptions that define a scenario into changes in owner behavior puts responsibility on the analyst rather than the model. Whether this is a disadvantage depends on the ability of the analyst to consistently and realistically perform this key step.

A disadvantage is that the model has no internal market or behavior feedback mechanism. This can lead to unrealistic fluctuations in harvest levels between periods. Since the model is simple, fast, and inexpensive, it is possible to alleviate this problem, with the analyst providing the feedback mechanism by adjusting behavior changes in an iterative manner to produce a reasonable harvest schedule.

Finally, the approach is currently an unconventional modeling strategy and has not had the degree of testing and scrutiny in its application relative to other approaches.

THE FRRAP SIMULATION APPROACH

To simulate the wide range of resource management behavior prevalent in California, forestland owners are characterized as belonging to one of several behavior classes. A behavior class represents landowners who share similar views regarding their land as an economic asset, have similar management objectives, face similar constraints that affect ability to invest, and, therefore, utilize similar management practices. The use of behavior classes adds flexibility in simulating differences in management between, for example, industrial forestland owners with and without sawmills, or between the variety of nonindustrial forestland owners. Examples of behavior classes include the intensive grower that produces a stable flow of raw material over time and invests heavily in regeneration and stand improvement practices, and the holder that owns land for a variety of reasons and does not actively manage for timber production.

Yield streams must be generated for each behavior class for inclusion in the simulation model. Since each class has well defined objectives and constraints, optimization methods can be used to project resource production and the resulting environmental consequences for each class. The key point is that optimization is performed initially only to generate yield

Table 1.--CALPLAN behavior class characteristics.

	Capital Asset Manager	Grower	Steward	Holder
Goals	High return on existing capital; high liquidity; diverse portfolio	Stable income, raw material supply; land stewardship	Multiple use; maintenance or enhancement of a variety of resource values; damage avoidance and mitigation	Primarily non-timber goals; homesites, recreation, investment, estate
Planning period	Short- to mid-term, 5-20 years	Mid- to long-term; 15-100 years	Mid- to long-term; 15-100 years	Short- to long-term; 5-100 years
Discount Rate	High	Moderate	Low to moderate	Low to moderate
Constraints	Few on harvest; cash flow and other investments; opportunities	Maintain material supply, income; capital reserves for future needs	Timber harvest cannot degrade other resource values	Shared constraint against regular harvesting
Management	Short conversion period, high basal area harvest	Moderate conversion period, moderate basal area harvest, stand improvements	Long conversion period, light basal area harvest, stand improvements, some areas withdrawn from harvest	No timber harvest

streams to incorporate into the CALPLAN simulation model. Yield streams are also generated for each possible change in ownership and/or behavior class in future periods. These changes can occur through direct land sales or transfers, or changing behavior in response to external forces.

CALPLAN is calibrated by deriving an initial distribution of forestland acres among behavior classes that results in levels of production consistent with what is currently observed at the county level. The calibrated behavior class pattern is constant for all scenarios. Scenarios are simulated by translating assumptions related to future political, economic, and social conditions into changes in ownership and behavior class structure. The ownership and behavior class changes drive the model, generating estimates of resource production and environmental consequences over time.

CALPLAN Forestland Owners

Major forestland owner groups are separated in CALPLAN in order to provide unique estimates of future resource production and condition, making it possible to target policies at acreage more specific than the entire forestland base. Four major forestland ownership groups are identified in CALPLAN: Forest Service, other public, timber industry, and nonindustrial private. Since Forest Service outputs are taken from draft management plans, the use of behavior classes for simulation purposes applies only to the other three ownerships.

CALPLAN Forestland Behavior Classes

Forestland behavior classes used in CALPLAN are based on previous work on California landowners (Casamajor et al. 1960, Romm and Washburn 1985, Romm et al. 1987, Teeguarden et al. 1960). Behavior classes are defined by four factors: dominant goals, length of planning horizon, real discount rate used in decision-making, and internal constraints on behavior. These four factors influence resource management-related investment and disinvestment decisions.

Four major behavior classes are used, with levels within each major class. The major classes are Capital Asset Managers, Growers, Stewards, and Holders. The four classes are described in the following section and summarized in table 1.

Capital Asset Manager

The Capital Asset Manager behavior class (CAM1-CAM3) is comprised primarily of national or multi-regional integrated forest product firms that aggressively manage their lands and move capital between regional operations. Mid-sized California forest products companies that are not primarily landown-

ers, but will occasionally purchase land for the timber inventory, may also be part of this class. Resort, residential, and commercial developers may also be included.

The primary timber harvesting, management, and investment behavior of Capital Asset Managers is driven by the strategic capital value of the existing timber inventory. The criteria for investment are modeled to reflect the spectrum of possible behaviors within this class. At one end of the spectrum are owners (CAM1) with extremely high rates of return and short planning horizons, who are likely to reinvest only the minimum required by law into timberland condition. At the other end are owners who aggressively manage their timberlands for current and future yield, sustaining high levels of investment in timberland (CAM3).

Grower

Large scale industrial tree farmers would generally be classified in the Grower behavior class (GROWER1-GROWER2). This class includes mid-sized, integrated California forest products companies, insurance firms and pension funds, and farmers and ranchers with forest woodlots.

Growers usually look to their forest lands for a sustainable income or supply of raw material over a mid- to long-term planning horizon. Two levels of growers (GROWER1 and GROWER2) are used to represent the range of investment within the class.

Resource Steward

Resource Stewards are primarily those owners whose land management behavior is driven by multiple use objectives, and timber production is not a dominant goal. This class includes rural homesteaders and wealthy, well-educated "new" landowners. In addition, many areas not available for conventional timber harvest, such as scenic corridors or some parks, are managed in a stewardship fashion.

The dominant goal can be a variety of individual or multiple goals, including wildlife habitat preservation, maintaining scenic areas, and improving recreational possibilities. Timber production can be one of the goals as well, but is not allowed to interfere with other objectives.

Holder

The Holder class consists of owners who, based on their own goals and constraints, feel that forest land with standing timber produces greater benefits in the near- to mid-term than if the timber were cut. Owners look to their lands for many non-income related benefits, such as amenity, recreational and wildlife values, capital appreciation of land and timber together for real estate value, as well as for a homesite. There are many varied goals and owner types from homeowners, recreation retreats, land speculators, developers, or estate trusts.

Behavior Class Yield Streams

Field plot and aerial photo data from the Forest Inventory and Analysis PNW Portland group, coupled with the FRRAP Geographic Information System, provided the basis to represent the current distribution and condition of forestland in terms of species composition, volume, site quality, and stocking levels. The data are used to derive a unique inventory structure for each region and owner combination.

The growth and yield component of the California Timber Supply (CATS) model (Krumland and McKillop 1987) provided a way to grow individual field plots into the future and simulate the range of management practices currently observed in California. The model has growth functions derived from remeasured trees from the FIA surveys, providing a consistent method of projecting growth for all species and locations in the state. Outputs from the CATS model include harvest, inventory, growth, and mortality by species group.

A computer program was linked to CATS that determines the Wildlife Habitat Relationships (WHR) cover type based on species composition, and successional stage based on tree size and crown closure for each FIA field plot as it is managed through time. This allowed a unique WHR type/successional stage structure yield stream to be derived for each region, owner, and management regime combination.

Initially, timber and wildlife habitat yield streams were generated using CATS for each management regime. Even-age regimes are defined based on the conversion period required to harvest existing merchantable stands, and regeneration intensity. Uneven-aged regimes are defined based on percent of basal area removed during 10-year entries, and whether stand improvement practices such as removal of suppressed trees and undesirable species are performed.

The characteristics of typical even- and uneven-aged management regimes used by each behavior class are shown in table 2. For example, the GROWER2 uses even-aged management consisting of a 50-year conversion period and intensive regeneration practices. Uneven-aged management for the GROWER2 consists primarily of removals of 33 percent of the basal area during 10-year entries, with stand improvement practices. Understocked and hardwood dominated areas are converted to fully stocked conifer stands over a 10-year conversion period using intensive regeneration practices.

Behavior class yield streams are derived based on proportionate use of management regimes by each class. Relative use of even- versus uneven-aged regimes varies by behavior class and by region. In the North Coast Region, even-aged management is more prevalent than in other regions of the state, for example.

Yield streams are also derived for behavior class and ownership changes. For example, land transferred from a nonindustrial holder to an industrial GROWER2 is simulated by growing the inventory to the mid-point of the period of transfer, and then applying the management regimes typical of the GROWER2 class.

Table 2.--Management regime characteristics by behavior class.

	Even-aged management		Uneven-aged management		Understocked & hardwood stands	
Behavior class	Conver. period	Regen. intensity	Basal area removal	Stand improv.	Conver. period	Regen. intensity
CAM1	10	Minimum	75%	No	10	Minimum[1]
CAM2	20	Minimum	50%	No	20	Minimum
CAM3	20	Intense	50%	No	10	Intense[2]
GROWER1	50	Minimum	33%	Yes	50	Minimum
GROWER2	50	Intense	33%	Yes	10	Intense
Steward	100	Intense	10%	Yes	100	Intense
Holder	No cut	--	No cut	--	--	--

[1]Minimum regeneration intensity for treatment of understocked and hardwood dominated stands implies that restocking is performed only if the operation can pay for itself.

[2]Intensive regeneration intensity for treatment of understocked and hardwood dominated stands implies that re-stocking is performed regardless of whether the operation can pay for itself.

Calibration

CALPLAN is calibrated to reflect current conditions, based on historical timber harvest levels, and current ownership and management patterns. Forestland is assigned to behavior classes to generate levels of outputs that are consistent with what is currently observed. The calibrated behavior class structure represents the ownership and management pattern for the decade 1980-1990, and provides a common basis for subsequent CALPLAN simulations.

Briefly, calibration was accomplished in a two-step process. First, initial behavior class proportions were estimated for each owner group in each county, based on ownership surveys, interviews, Department of Forestry and Fire Protection timber harvest plan records, and Board of Equalization timber tax harvest records. The process was a county-by-county, owner-specific, intensive allocation of proportions across behavior classes consistent with existing, available information. These proportions were then systematically adjusted so that the resulting timber harvest levels matched the 1978-1985 average annual harvest for a particular owner group in a particular county.

Scenario Simulation

Scenario simulation is a four-step process. First, the future economic, social, and political climate of the scenario is defined. Based on the scenario, qualitative changes in owner objectives are identified. The third step involves translating the qualitative changes into actual quantitative changes in the relative proportions of acres in different behavior classes. Fourth, the impacts of these changes are estimated with the CALPLAN model.

A basic premise of CALPLAN scenarios is that future conditions depend on how forestland owners are likely to respond to a wide array of market and non-market trends, particularly regarding current harvest and investment in future productivity. Within this context, current and future stumpage and lumber prices along with resource capability play a role, but are not the sole determinant of investment or future timber supplies. In certain circumstances, social and political considerations and trends play stronger roles in landowner behavior. Investment and disinvestment decisions will be based on the interaction of these trends. The local and regional variation in the trends will also influence future conditions.

Future trends that are likely to affect landowner objectives and behavior are quantified to the extent possible, or described qualitatively. Quantification and description is based on a variety of sources, including government and private statistics and projections, academic research, interviews and contacts with private industry, Forest Service, Department of Forestry and Fire Protection, other agencies and interested groups. The 1987 FRRAP Assessment provides most of the historical detail on which trends are based. This first step serves to define the context of the scenario.

The second step involves projecting how landowner objectives and behavior may change within the context of the current scenario. Some trends are indicative of shifts in owner objectives. Depending on their circumstances, landowners can be expected to change their behavior in response to projected trends. For example, in a simple scenario with rapidly rising stumpage prices in the short-run, some landowners can be expected to respond by increasing harvesting activities. The degree of change in response to price trends will vary by county based on unique social and political characteristics of local communities.

The third step involves making explicit changes in the relative proportions of land held and managed by different owners and behavior classes. These changes arise through direct land transfer or modification of the objectives and/or constraints of individual owners. The changes are made on a county-by-county basis, from the calibrated behavior class pattern.

Finally, the proportions are entered into CALPLAN and the results are examined. Iterations may be necessary to incorporate feedback responses consistent with the trends that constitute the scenario. The purpose of this fourth step is not to produce a predetermined output level but to generate trends in output flows that are consistent with the scenario.

The strength of the scenario simulation process lies in the explicit nature of assumptions about trends, changes in land use, geographic variability, and the rationale behind such choices for the scenario. Consequently, the strength of simulations depends on the plausibility of any particular scenario, and the consistency with which it is implemented.

ALTERNATIVE SCENARIOS

Two scenarios will illustrate the CALPLAN simulation process. For simplicity, the current discussion focuses on non-industrial lands in the North Coast Region of California. Non-industrial owners have less than 5,000 acres of forestland and no full time timber management staff. The North Coast Region, consisting of Del Norte, Humboldt, Mendocino, and Sonoma Counties, accounts for a substantial portion of the state's timber output, but is also in a state of transition away from timber dependency.

The first scenario has been extensively developed as part of the Assessment. The second scenario demonstrates a simple "what if" analysis that could be used for policy, sensitivity, or trade-off analysis.

Scenario One: Continuation of Current Trends

For the continuation of current trends scenario, the following major factors are expected to influence future timber supply in California:

Social factors: diversification and internationalization of the California economy; increased demand for a wider variety of forestland outputs; continued settlement, conversion, and fragmentation in the forest fringe; and higher reservation price for timber from nonindustrial lands associated with higher relative values placed on other ownership attributes.

Political trends: increasing institutional conflicts between levels of government, agencies, and interest groups; increased concern and litigation over timber harvesting activities; and decreasing political influence of natural resource commodity industries in an urban, high technology, service-oriented economy.

Market trends: slower long term growth in demand and real prices for lumber and wood products, with continued short-term volatility; continued competitive pressure from the Pacific Northwest, Canada, and the Southeastern U.S.; technological improvement in sawmilling and manufacturing; decreased comparative advantage from specialty old-growth products; little development of new products and markets; and scarce capital for investment due to lower profit margins and high budget and trade deficits.

If current trends continue, then a less than favorable economic and political climate for high investment levels in timber production in California can be expected, over the long-term. Statewide, investment in intensive timber production is likely to decrease over the next two decades, due to rising production costs and regulatory constraints, coupled with slow to moderate real price increases for lumber. However, landowner behavior can be expected to vary by region within the state.

In the North Coast, biological and economic conditions will be relatively more conducive to active forest management. In the short term, timber harvest and investment should remain relatively high, on both industrial and nonindustrial lands. On the other hand, continued population growth, changes in local attitudes, especially among landowners neighboring areas to be harvested, and heightened local and statewide attention paid to remaining old-growth stands in private ownership, are likely to affect landowner decisions regarding investment in intensive management, particularly in Sonoma and Mendocino Counties. Doubts by owners about the probability of managing and harvesting timber over the long-run may dampen investment, as will any rise in production costs not offset by rising lumber prices. Although nonindustrial lands may be harvested as they change hands, new owners are likely to have different values and higher reservation prices than previous owners.

Scenario Two: Active Nonindustrial Forestland Management

A second, relatively simplistic scenario has been developed to illustrate the "what if" approach, focusing on nonindustrial private forestlands in the region. It demonstrates how a scenario would be modeled to reflect active timber management by a substantial portion of the nonindustrial sector, for example, in response to a successful policy or program. It also shows how sensitivity analysis, with respect to behavior class changes, could be done in CALPLAN.

SCENARIO RESULTS

Behavior Class Changes

Proportionate changes in acreage between different behavior classes were made, on a county-by-county basis, to simulate landowner responses for each scenario. Table 3 presents the net effect of the two scenarios on land ownership by behavior class for nonindustrial forestland owners in the North Coast.

If current trends continue, nonindustrial forestland owners would be expected to increase timber management activities, responding to a growing inventory, active industry log buying programs, and high values represented by redwood. The amount of land owned by the Holder class would be expected to decline, with increases in the Grower and Steward classes. Sixty-five percent of the nonindustrial forestland would remain in the Holder class, however. For the second scenario of more active nonindustrial timber management, substantially higher proportions of land would shift to the CAM3 and GROWER2 behavior classes, and a lower proportion would be in the HOLDER class. Table 4 shows how these proportions would vary by county.

Timber Inventory, Growth, and Harvest

Projected timber inventory, growth, and harvest based on the simulated behavior class changes for the two scenarios are

Table 3.-- Proportion of nonindustrial private forestland acres, by behavior class, North Coast Region, for two scenarios.

Scenario	Behavior class	Percent of acres 1980-1990	1990-2000	2000-2010
Scenario #1	CAM1	0%	0%	0%
	CAM2	3%	3%	3%
	CAM3	6%	6%	6%
	GROWER1	6%	11%	12%
	GROWER2	0%	2%	3%
	Steward	4%	7%	10%
	Holder	80%	71%	65%
	Total	100%	100%	100%
Scenario #2	CAM1	0%	0%	0%
	CAM2	3%	2%	2%
	CAM3	6%	17%	28%
	GROWER1	6%	5%	3%
	GROWER2	0%	12%	25%
	Steward	4%	3%	2%
	Holder	80%	60%	40%
	Total	100%	100%	100%

Table 4.-- Variation in selected behavior class proportions by county, for two scenarios, for nonindustrial private forestland, North Coast Region.

	1980-1990	1990-2000		2000-2010	
		Scenario #1	Scenario #2	Scenario #1	Scenario #2
North Coast					
CAM3	6%	6%	17%	6%	28%
GROWER2	0%	2%	12%	3%	25%
Holder	80%	71%	60%	65%	40%
Humboldt County					
CAM3	7%	7%	18%	8%	29%
GROWER2	0%	4%	12%	5%	24%
Holder	79%	67%	60%	59%	40%
Sonoma County					
CAM3	4%	2%	15%	0%	27%
GROWER2	0%	2%	13%	4%	25%
Holder	89%	91%	67%	93%	45%

presented in table 5. Average harvest is greater under the second scenario, while inventory is lower. Growth is also lower until the later decades.

Wildlife Habitat

Results of a CALPLAN simulation also include acreage by county, owner, WHR cover type, and successional stage for the beginning year of each decade. The eight successional stages carried in CALPLAN are defined based on quadratic mean diameter (QMD) range and percent crown closure. Since the detail of the acreage data makes it difficult to analyze, Habitat Suitability Index (HSI) models are used to translate availability of the habitat structure into overall suitability for selected species.

In table 6, the approach is demonstrated for a single species, the fisher *(Martes pennanti)*. Each WHR type and successional stage has a unique suitability rating (0 to 1) for the fisher, based on feeding, breeding, and cover requirements. The fisher prefers dense stands of larger trees, with stage 8 being rated .93 out of a possible 1.0 rating.

Overall suitability is derived as the summation over all eight stages of the stage acreage times the stage HSI rating. For 1980-1990, the overall suitability rating is 573,000 habitat units.

Table 7 presents the initial and subsequent (year 2020) habitat structure on nonindustrial lands for the two scenarios. Under both scenarios, overall habitat suitability for the fisher increases, reflecting the buildup of inventory, especially in stages 6 and 8. The increase is greater under scenario 1.

CONCLUSION

The relatively simple, explicit methodology used in the FRRAP simulation approach is a positive step in assessment and policy analysis for a large, complex state such as California. It allows incorporation of different kinds of information from a

Table 5.-- Projected conifer inventory, annual average harvest, and average annual net growth, thousand board feet (MBF), for nonindustrial private forestlands, North Coast Region, for two different scenarios.

Period	Inventory (mbf)	Harvest (mbf)	Growth (mbf)
		Scenario #1	
1980-1990	14,733,880	96,404	326,311
1990-2000	16,914,432	148,816	355,020
2000-2010	19,028,016	156,431	372,945
2010-2020	21,464,000	133,006	403,688
2020-2030	24,469,728	115,396	445,862
2030-2040	27,819,024	125,373	464,767
2040-2050	31,446,896	104,316	490,497
		Scenario #2	
1980-1990	14,733,056	96,460	326,254
1990-2000	16,315,160	258,163	344,791
2000-2010	16,511,136	378,150	330,718
2010-2020	16,697,696	249,362	334,107
2020-2030	18,239,392	161,847	385,441
2030-2040	20,946,688	160,711	478,578
2040-2050	24,119,728	264,388	581,127

Table 6.-- Habitat Suitability Index (HSI), acres of habitat, and habitat units, by stage, for fisher *(Martes pennanti)*, nonindustrial private forestland, North Coast Region, 1980.

Stage	HSI rating	1,000 acres	1,000 habitat units
1	0.00	15	0
2	0.00	64	0
3	0.05	169	8
4	0.15	80	12
5	0.22	249	55
6	0.79	539	426
7	0.28	57	16
8	0.93	60	56
	Total	1,233	573

Table 7.-- Habitat units (in thousands) for fisher *(Martes pennanti)*, 1980-1990 and 2020-2030, for two scenarios, for nonindustrial private forestland, North Coast Region.

Stage	1980-1990	2020-2030 Scenario #1	2020-2030 Scenario #2
1	0	0	0
2	0	0	0
3	8	7	7
4	12	15	21
5	55	20	11
6	426	495	461
7	16	7	7
8	56	104	95
Total	573	648	602

wide variety of sources. The capabilities of the system will continue to improve as better information becomes available. For example, timber supply projections can be updated as additional information is received from Timber Harvest Plans, Board of Equalization harvest data, and various studies related to owner behavior and management practices. Serving as a central collection point for California resource management information, it also points to areas where existing data sources need to be improved or expanded.

The use of HSI models in conjunction with CALPLAN allows for some aggregate wildlife impact analysis, but is far from complete. Translating changes in total habitat units into impact on species populations is difficult at best. Future work of FRRAP will concentrate on generating separate estimates of total habitat units for feeding, breeding, and cover. This may allow better analysis for species where, for example, it is known that breeding habitat is the limiting factor.

Concentrating on acreages of potentially available habitat also neglects critical elements such as spatial considerations, species interactions, special habitat requirements such as snags or water, the effect of human intervention from recreation, roads, and rural housing, and effects of environmental contaminants. Although some data for these factors is available, for example the FRRAP GIS for spatial considerations, professional expertise will continue to play an important role in the absence of sufficient data and methods to simulate all these factors.

The simulation approach developed by FRRAP represents a unique approach to simulating future conditions for a wide variety of scenarios. The first scenario, based on the continuation of current trends, depicts only one of a number of possible futures for California. As such, it is not a hard or certain prediction of the future course of events, but is a simulation of what is likely to occur if the trends in the scenario do occur. Attempts to predict the future cannot be done with certainty, precisely because of the multitude of influences. The second scenario represents a different future for the state, reflecting a contrasting set of assumptions of future conditions. By using the scenario approach, forest policy can be effectively focused to take an active role in shaping future conditions in California.

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Alternative Specifications and Solutions of the Timber Management Portfolio Problem

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Abstract.--This paper studies several ways in which timber management portfolio problems can be specified and solved. Although portfolio analysis is very common for financial investments, and to some degree for agricultural investments, little work has been done in this area for timber management. Mills and Hoover (1982) solve a timber, agricultural, and financial securities portfolio using the MOTAD method of Hazell (1971). Thomson (1987) uses quadratic programming to solve timber management portfolios for the South and Midwest.

This paper uses the annual timber management returns for selected Midwestern and Southern species developed by Thomson (1987) to compare the following methods for solving timber management portfolios: (1) quadratic programming, (2) classical optimization, (3) MOTAD, (4) Sharpe's single-index model, (5) stochastic dominance, and (6) growth optimal portfolios. The underlying assumption for each alternative is that the timber species is managed in a fully regulated condition for producing sawtimber. All computer analysis was done on an MS-DOS computer.

Quadratic programming correctly solves the standard portfolio problem, and low cost microcomputer software will solve timber portfolio problems quickly. Classical optimization, although straightforward, does not appear to be well suited for timber portfolios as negative portfolio weights are common, and there are no secondary markets for timber investments. Although the solution method can be adjusted when negative portfolio weights appear, it is easiest to use another solution method. The MOTAD linear approximation method appears to work quite well and is a useful alternative when quadratic programming software is unavailable. The single-index model is another approximation technique developed to relieve the computational burden of solving large portfolio problems. For the small problems encountered in timber management portfolios, it is easier to solve a quadratic program than to perform the necessary regressions for the single-index technique. A side benefit of using the single-index approach, however, is that the estimated betas are a good measure of the relative riskiness of an investment.

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To respond to criticisms of the standard portfolio analysis, we also analyze the stochastic efficiency and optimal growth properties of the portfolios. All of the portfolios were found to be second degree stochastically efficient, thus the standard mean-variance analysis appears to yield stochastically efficient results. In analyzing the long run returns that can be expected on the portfolios we found that expected long run returns lower than expected single period returns, and that maximizing expected single period return does not maximize long run return. Risk aversion in the short run is required to maximize long run returns.

Introduction

Since the pioneering work of Markowitz (1952), portfolio analysis has become a standard part of many financial decisions. Its basic premise has long been known, that is, don't put all of your eggs into one basket. Markowitz formalized the problem as minimizing the variance (or standard deviation) for any level of expected return. This was called efficient investing. A key finding of this work was that investments that may appear undesirable on their own (too risky given its expected return), may be valuable components of a portfolio of investments. Investments with rates of return that have little correlation with rates of return of other investments provide low portfolio risk. Economics and financial literature has established much knowledge on the subtleties of risk-return efficient investing including assessment of investors feelings toward risk, the statistical distributions of rates of return, and the market equilibrium outcomes when investors optimally diversify their holdings.

The forestry literature also has recognized risk in forest management for some time. Much of the earlier work has centered on the uncertainty associated with forest inventory sampling (Arvanitus and O'Regan 1967, Hamilton 1970). Financial uncertainty of timber management, however, has also been studied. Dowdle (1962) framed Markowitz's idea for evaluating timber investments and applied this to a trade-off between the present net worth per tree at rotation and its variance. Marty (1964) proposed using dominance criteria for selecting timber management alternatives under risk.

Mills and Hoover (1982) used portfolio analysis to determine whether it was rational for Indiana farmers to include timber investments in their land use and financial portfolios. Although the rates of return from timber investments were lower than those of agricultural investments, the lack of correlation between these investments allowed both to be included in some efficient investment portfolios. Thomson (1987) included portfolio analysis in his comparisons of the financial risks of timber growing between the South and Midwest.

In addition to the applications of using portfolio analysis to determine the desirability of including various timber components for portfolios, we also feel that this approach might be used to develop measures of relative risk based upon variations in the rates of return for alternative forestry investments. These alternatives might include buying forest land, planting or improving certain tree species, developing genetically improved trees, thinning, pruning, fertilizing, or growing mixes of pulpwood, sawtimber, or veneer logs on one or more sites. Variation in returns could in itself provide a summary measure of risk for alternative forestry investments and could be used to develop an efficient portfolio of forestry investments which would minimize risk for given rates of return. Further investigation of its use in this context is warranted.

The standard approach for solving efficient portfolio frontiers for this paper is quadratic programming as was used by Thomson (1987). Another approach uses the classical optimization technique of Lagrangian multipliers. The MOTAD approach of Hazell (1971) is another alternative. Single-index methods (Sharpe 1963) have been suggested as an easier approach to estimating the efficient portfolio. Collins and Barry (1986) have suggested using the single-index model to determine efficient farm management portfolios. The use of stochastic dominance has been proposed as an alternative to mean-variance portfolio choice. Bawa (1982) summarizes a number of examples the financial economics literature and Anderson et al. (1977) give examples from agricultural economics. Grauer and Hakansson (1986) suggest that the appropriate portfolio selection focus is long run risk and return, rather than single period risk and return.

Given this variety of ways to approach portfolio problems, our paper compares these methods for developing timber management portfolios. It develops the efficient risk-return trade-off each one proposes, compares the difference in solution methods, and describes under what circumstances each may be a viable alternative for solving timber management portfolios.

The Data

Thomson (1987) derived a data set to solve the questions posed concerning financial risk between the Midwestern and Southern timber management portfolios. Because of the time consuming nature of developing the periodic returns to timber management, and because the focus of this paper is to compare among several methods of solutions with the same data set, we decided to use that data set for the analysis presented here. The data for calculating efficient portfolios consists of period by period rates of return for each timber management investment being considered. The investments considered in this paper are fully regulated sawtimber producing forests of the several species. Midwestern species include red pine, white pine, aspen, and red oak. Southern species include southern pine, ashes, gums, and oaks. The annual rate of return for each species was calculated as shown in Thomson (1987):

$$R_t = [(P_tG + P_tH - C)/P_{t-1}G] - 1$$

where:

Pt = stumpage price in period t,

H = Volume harvested annually from the fully regulated forest,

G = growing stock index, which is constant from period to period for a fully regulated forest,

C = the annual cost of managing the forest.

Combining price, growth and yield, and management costs information, one can calculate the periodic return for any given fully regulated forest. P_tG is the current value of the forest growing stock (like the price of a stock). $P_{t-1}G$ is last years value of the forest growing stock (like last years stock price). The monetary dividend the forest has paid is the value of the harvest, P_tH, minus the annual forest management costs.

Growth and yield information and forest management strategies and costs were garnered from a variety of sources as noted in Thomson (1987). Annual sawlog stumpage price data from 1960-1980 for pine, ash, oak, and gums in Louisiana was found in Ulrich (1985). Lothner et al. (1982) provided similar data for white pine, red pine, aspen, and red oak in Minnesota. All price and cost data was converted to real dollars, thus, all rates of return reported here are real rates.

Analysis

The objective for most of these techniques is to minimize the level of risk for any expected return. The risk of a portfolio is usually measured as its standard deviation (or variance). The constraint on the portfolio is that the sum of the individual investment alternatives must sum to the total portfolio which is generally normalized at one. To trace out the individual points of the efficient frontier requires that one vary the expected return on the portfolio from the minimum variance rate of return

through the rate of return on the investment with the highest expected rate of return. The portfolio problem may be formally stated as (Francis and Archer 1979):

$$\text{Minimize} \quad \sum_i \sum_j X_i X_j \sigma_{ij}$$

$$\text{subject to:} \quad \sum_i X_i E(R_i) >= R^*$$

$$\sum_i X_i = 1$$

where X_i's are the portfolio weights, σ_{ij} is the covariance between investment i and j, and $E(R_i)$ is the expected return from investment i. The objective is to minimize the risk (defined as variance of returns), subject to earning a given level of return (R*), while requiring that the portfolio weights sum to 1 (full investment in the given alternatives). All computing was done on an MS-DOS microcomputer.

Quadratic Programming

Where non-negative portfolio weights are required, the standard portfolio problem can be solved using quadratic programming. From the returns calculated in each period over the sample period, the mean return and the variance for each timber investment was calculated, as was the covariance for each pair of investments. The minimization of variance is the quadratic object function subject to the linear constraints of having the portfolio weights add up to one, and the portfolio return equal a set level. After setting up the inputs, the expected return was varied parametrically to trace out the efficient frontier. The solutions were derived using the QPROG software (Saigal 1986). Figure 1 shows the efficient portfolios frontier in mean-standard deviation space for our data set. This result, also found in Thomson (1987), will be referred to as the standard analysis in this paper. Table 1 shows timber investment weights for the minimum risk portfolios with an expected return of 6, 7, 8 and 9 percent.

Classical Optimization

Classical optimization solves the portfolio problem presented above by setting the problem in the Lagrangian format (Francis and Archer 1979). Taking first derivatives of the series of equations yields a system of linear equations that can be solved using matrix algebra. The portfolio rate of return is varied and the system resolved to trace out the efficient frontier. The mathematical calculations were done using the matrix routines of the Smart Spreadsheet[2] (Innovative Software 1986). The frontier developed using classical optimization is shown on figure 1.

[2]*The use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the U.S. Department of Agriculture to the exclusion of*

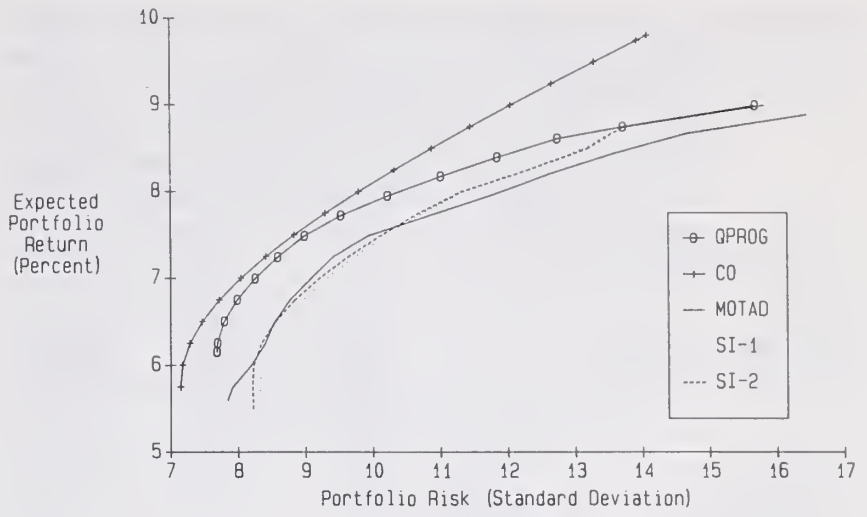


Figure 1.-- Expected portfolio return (percent) versus portfolio risk (standard deviation) calculated by the standard analysis (QPROG), classical optimization (CO), MOTAD method (MOTAD), Sharpe's diagonal method (SI-1), and Elton and Gruber's covariance approximation (SI-2).

Figure 1 shows that the frontier developed by classical optimization has a higher rate of return for any level of risk than the standard analysis discussed above. This result is expected as this is the least constrained approach to portfolio analysis. By analyzing the portfolio compositions (see table 1), however, one will see that all portfolios calculated by this method contain negative weights. In other words, some of the investments (say in southern pine or gum) are financed through having negative weights in other investments (such as red pine and southern oak). Foresters know, however, it is impossible to have negative red pine forests. To have negative red pine investments would require financial markets in such forests that would allow "short selling," that is selling of a security one does not own and investing the proceeds in another security. It is unlikely that financial markets in this sense will arise in timber investments so a portfolio which contains negative investments is not realistic. Classical optimization is a good technique for solving portfolio problems when negative portfolios do not enter the optimal solution, or for those investments where selling short is an alternative. For timber portfolios it appears inappropriate due to negative weights which are unlikely to be realizable in timber investments.

MOTAD (Minimization of Total Absolute Deviations)

Linear programs are an efficient method of solving a constrained set of equations and typically do not allow negative decision variables. The use of linear programs is wide spread, as is the availability of computer solving routines making it seem an attractive alternative for solving portfolio problems. The objective of minimizing portfolio variance, however, is non-linear. Hazell's (1971) MOTAD method replaces the objective of minimizing the variance, with the linear objective of minimizing of the absolute deviations from the mean. While this is a less efficient method of minimizing deviations (compared to

Table 1.-- Portfolio weights of various species to yield rates of return of 6, 7, 8, and 9 percent at minimum risk calculated by the standard analysis (QPROG), using classical optimization (CO), using the MOTAD method (MOTAD), using Sharpe's diagonal single-index model (SI-1), and using Elton and Gruber's variance-covariance estimation technique (SI-2).

Species	QPROG	CO	MOTAD	SI-1	SI-2
		-For 6 percent expected return-			
Red pine		-0.178			
White pine		0.066			
Aspen	0.138	0.150	0.114	0.067	0.080
Red oak	0.081	0.101	0.002	0.032	0.038
So pine	0.236	0.348	0.220	0.171	0.165
Ash		0.077		0.092	0.120
Gum	0.545	0.761	0.664	0.307	0.270
So oak		-0.325		0.331	0.326
		-For 7 percent expected return-			
Red pine		-0.184			
White pine		0.075			
Aspen	0.127	0.153	0.097	0.043	0.051
Red oak	0.078	0.100		0.025	0.029
So pine	0.445	0.533	0.391	0.433	0.433
Ash	0.242	0.334	0.317	0.179	0.189
Gum	0.108	0.653	0.196	0.165	0.154
So oak		-0.664		0.155	0.145
		-For 8 percent expected return-			
Red pine		-0.190	0.097		
White pine	0.053	0.083			
Aspen	0.047	0.156	0.016	0.016	0.019
Red oak	0.055	0.099		0.017	0.018
So pine	0.697	0.718	0.501	0.698	0.704
Ash	0.148	0.591	0.386	0.261	0.254
Gum		0.544		0.007	0.005
So oak		-1.002			
		-For 9 percent expected return-			
Red pine		-0.195	0.347	0.026	0.020
White pine	0.347	0.091		0.329	0.334
Aspen		0.159			
Red oak		0.098			
So pine	0.653	0.904	0.653	0.645	0.647
Ash		0.847			
Gum		0.436			
So Oak		-1.340			

using the variance) it appears to have successfully solved many problems to which it has been applied (e.g., Mills and Hoover 1982). In place of the variance-covariance matrix, one uses a matrix of deviations from the mean for each data period. This data was set up using the Smart Spreadsheet, which was then written into a Data Interchange Format (DIF) which was read in to the Kinetics Linear Programming System[2] (Kinetics Software 1984) for solving the problem. The required rate of return was varied parametrically to trace out the efficient frontier.

Typically when using the MOTAD method, one would trace out the efficient frontier in mean-absolute deviation space, rather than mean-standard deviation space. To present consistent results in this paper, however, we used the portfolio weights determined from the MOTAD solutions along with the full variance-covariance matrix to calculate the true portfolio variance which would result from these weights. It is these values that are shown as the MOTAD portfolios and plotted on figure 1. Comparing the MOTAD results to the quadratic programming results shows that MOTAD gives a reasonably close approximation of the minimum risk portfolios. Results of usefulness of MOTAD depend on how closely it tracks to the QPROG solution. It is certainly easier to do the MOTAD calculations as one does not need to compute a variance-covariance matrix. For those who have familiarity or availability of only linear programming computer codes, it serves as a good approximations tool. With the availability of microcomputer quadratic programming code, however, it may be worthwhile to choose the quadratic programming solution.

Sharpe's Single-Index Model

To use either classical optimization or quadratic programming requires the variance-covariance matrix for the investments being considered. When choosing among a large variety of investments calculation of this matrix can be difficult. The single-index model overcomes the difficulty of calculating the variance-covariance matrix by using linear regressions on an index to estimate appropriate values for the variance-covariance matrix.

Sharpe (1963) showed his single-index could be applied at very low cost, relative to the standard quadratic programming codes available then. Moreover, he found that the relatively few parameters used by the model led to very nearly the same results obtained with larger sets of relationships among securities, and that the low cost model provided an attractive candidate for initial practical applications of the Markowitz technique. Sharpe maintained that the "diagonal" or single-index model had two virtues: "it is one of the simplest that can be constructed without assuming away the interrelationships among securities,and there is considerable evidence that it can capture a large part of such interrelationships." The major assumption of the model is that the returns of various securities are related only through common relationships with some basic underlying factor. The return from any security is determined solely by random factors and this single factor.

Collins and Barry (1986) employ the single-index model using expected returns from 12 crops grown in the Imperial Valley of California. They defined the aggregate variable (the index) as an unweighted average of the returns on the 12 crops over a 17-year period. The single-index Betas and the expected returns provided the input data for deriving risk efficient crop

combinations which closely approximated those derived with a full variance-covariance matrix. We performed a similar analysis with the timber management returns using the unweighted average price of all timber species to calculate annual percent changes in average price which we used as our index. We used the diagonal covariance matrix technique and QPROG to determine risk minimizing portfolio weights for a given rate of return. We then took those portfolio weights and calculated the true portfolio variance using the full variance-covariance matrix. This result is presented as SI-1, on figure 1 and in table 1.

Elton and Gruber (1981) suggest an alternative approach to estimating the single-index model which also simplifies the estimation of the covariances. From the regressions performed for the above model, one can estimate the covariance of investment i, and j, as their Beta estimates times the variance of the market. We also used this approach for estimating the variance-covariance matrix and solved the portfolio problem using QPROG. From the resultant portfolio weights, we calculated the true portfolio variance using the full variance-covariance matrix. This result is presented as SI-2, on figure 1 and in table 1.

Either single-index model gave reasonably good results in predicting the true efficient frontier. Better results might be garnered through use of a superior index, or through use of multiple indices. At higher risk levels, they closely approximate the standard frontier. For the small problems that are typically analyzed as timber management portfolios (small number of candidate species), there is little difficulty in estimating the variance-covariance matrix using microcomputers. It is more time consuming to run the series of regressions for the single-index model than to calculate covariances thus the portfolio calculation is better left to the standard method.

Sharpe (1963) was primarily concerned with reducing the computational burden of including a large number of securities in a financial portfolio. Collins and Barry (1986) employed this approach to reduce the complexity of portfolio analysis to that within the capabilities of farm operators or advisors using 8 bit microcomputers to develop efficient portfolios for a relatively few crop production alternatives. Although their primary concerns have been alleviated by the current availability of efficient quadratic programming techniques, and more advanced microcomputers, our analysis of the single-index model led to several insights to explicit consideration of risk in forestry investment decisions.

Thomson (1987) found that Betas derived from regressing the returns to his eight forestry investments on the Standard and Poors Composite Index returns were not significant (table 2). This result suggests all timber investments have low market risks. Selecting among timber investments, however, Thomson addressed through portfolio analysis. Performing the regressions on an index which would yield statistically significant Betas will produce a measure of the relative riskiness of the various timber management investments. We found that Betas based on his return data and the average of price returns as a single-index were significant and gave an indicator of the

Table 2.-- Mean returns, standard deviations, betas, t values, and R squares for the standard and poors composite index and selected timber growing investments, regressed against this index.

Location	Species	Mean return	Standard deviation	Beta	t statistic	R squared
New York	S&P 500	0.0311	0.1167	1.00		1.00
Midwest	Red pine	0.0951	0.3002	-0.69	-1.34	0.09
Midwest	White pine	0.0981	0.2955	-0.91	-1.87	0.16
Midwest	Aspen	0.0367	0.2912	-0.47	-0.91	0.04
Midwest	Red oak	0.0553	0.2973	-0.49	-0.94	0.05
South	Pine	0.0857	0.1365	-0.07	-0.28	0.00
South	Ash	0.0698	0.1277	-0.14	-0.64	0.02
South	Gums	0.0555	0.1000	-0.07	-0.39	0.01
South	Oaks	0.0534	0.0976	-0.12	-0.72	0.03

variability and relative risk of his alternative forestry investments. Table 3 presents the results of the single-index regressions. The high Betas for white and red pine suggest these timber investments are relatively risky. The negative and non-significant beta for aspen shows it is the least risky. The portfolio weights shown in table 1 show how red and white pine enter only the riskiest portfolios, and that aspen enters the more risk free portfolios.

To further simplify the analysis of risk in timber management investments, we investigate the effect simply considering the price variation rather than the returns variation. Price variation can be analyzed by simply obtaining price series data rather than using the more involved analysis of constructing normal forests and determining the return from managing them. A series of returns of the form:

$$R_t = (P_t/P_{t-1}) - 1$$

was used as the dependent variable in regressions against the average price index described above. The results of these regressions are presented in table 4.

Table 3.-- Mean returns, standard deviations, betas, t values, and R squares for average annual price changes (the index) and timber management returns from selected timber growing investments regressed against this index.

Location	Species	Mean return	Standard deviation	Beta	t statistic	R squared
Both	Index	0.0336	0.1167	1.00		1.00
Midwest	Red pine	0.0951	0.3002	2.25	7.62	0.76
Midwest	White pine	0.0981	0.2955	2.14	6.69	0.71
Midwest	Aspen	0.0367	0.2912	-0.09	-0.16	0.00
Midwest	Red oak	0.0553	0.2973	0.44	0.75	0.03
South	Pine	0.0857	0.1365	0.82	4.13	0.49
South	Ash	0.0698	0.1277	0.83	4.91	0.57
South	Gum	0.0555	0.1000	0.58	3.94	0.46
South	Oaks	0.0534	0.0976	0.55	3.66	0.43

Table 4.-- Mean returns, standard deviations, betas, t values, and R squares for average annual price changes (the index) and annual price changes of selected timber species.

Location	Species	Mean return	Standard deviation	Beta	t statistic	R squared
Both	Index	0.0336	0.1167	1.00		1.00
Midwest	Red pine	0.0514	0.2864	2.15	7.66	0.77
Midwest	White pine	0.0542	0.2819	2.04	6.73	0.72
Midwest	Aspen	0.0364	0.2832	-0.07	-0.13	0.00
Midwest	Red oak	0.0516	0.2890	0.44	0.76	0.03
South	Pine	0.0471	0.1277	0.76	4.11	0.48
South	Ash	0.0394	0.1235	0.79	4.70	0.55
South	Gum	0.0292	0.0969	0.55	3.74	0.44
South	Oaks	0.0326	0.0947	0.51	3.47	0.40

The beta values in table 4 closely correspond to the beta values of table 3, suggesting that the simple technique of using returns estimated from price variation will give insights into the relative riskiness of various timber investments. Several good time series of prices for various tree species and products are available. Price variations regressed on an appropriate single-index can provide initial estimates of risk relative to returns for a wide range of timber investments.

Stochastic Dominance

One of the criticisms of mean-variance portfolio analysis is that a mean-variance efficient portfolio could be dominated by some other portfolio. A rational decision maker would never choose a dominated portfolio, although the mean-variance portfolio analysis might indicate either as acceptable. Individual investment opportunities can be evaluated as can portfolios to determine whether they are stochastically efficient dominated.

Several levels of stochastic efficiency have been proposed (Bawa 1975). First degree stochastic efficiency, or absolute dominance as it is also called, is a formalization of the dominance criteria proposed for timber investments by Marty (1964). The basic criteria for first degree stochastic dominance is that more is preferred to less so a first evaluation on investments is to compare their expected values. An investment with a given expected value can never dominate an investment with a higher expected value, although it might also not dominate an investment with a lower expected value. For absolute dominance, the dominating asset must also have a return that is greater under all states of nature.

Because few investments are absolutely dominated, other less restrictive measures of dominance have been applied. Second degree stochastic dominance adds the criteria of risk aversion to that of more being preferred to less. Risk aversion is a part of the implicit criteria of portfolio analysis, for if investors were risk neutral, the investment with the highest expected rate of return would always be chosen. Second degree stochastic dominance (SSD) requires that the area under the integral over expected return of the dominating probability distribution be less than or equal to the area under the other distribution at all points (see Bawa 1975). Pair-wise comparisons are made among investments to determine if some are dominated. As noted by Anderson et al. (1977), a first pass at these comparisons can be made by looking at the lowest observed return for each investment. If the portfolio with the higher mean also has a probability of a lower return, it cannot SSD dominate the investment with the lower expected return. When this test fails, then a more complete pair-wise comparison must be made. We looked at the lowest observed return for each of the portfolios calculated for the standard analysis and found that as the means increased, the lowest returns decreased showing that all points tested on the efficient frontier were also SSD efficient. As a result we did not have to resort to the more robust method of pair-wise comparison of all portfolio distributions. From this test it appears that timber portfolios which are mean-variance efficient will also be SSD efficient.

Growth Optimal Portfolios

Another criticism of the standard portfolio problem solved above is that it maximizes the expected single period return for any desired level of risk. Most investors, however, can be expected to focus more on long term wealth accumulation than on single period gains. Grauer and Hakansson (1986) present a method to develop portfolios that maximize the expected long run wealth gains for various levels of investor risk tolerance. To respond to the issue raised by Grauer and Hakansson, we model the long run expected return and variance for the standard portfolio frontier developed above. We employ a stochastic simulation technique. Grauer and Hakansson by contrast use a non-linear optimization method.

The essence of the long run problem is this. If one chooses a given portfolio and holds it for a long time, what is the expected rate of return and variance for that portfolio over the long haul. Binkley (1981) has shown that the long run variance for a given investment will be much lower than its single period variance. What is less apparent though, is that long run rates of return may be lower than the expected single period rate of return. In this situation, long term wealth accumulation may be higher from less risky portfolios or in other words, risk aversion in the short run can lead to higher long term wealth accumulation.

The simulation model used in this portion of the study assembled the returns to each portfolio of investments for each period, and assumed this was the true distribution of returns. Each observed return was assumed equally likely to occur in any year in the future. The relative wealth change (1 plus the annual rate of return) one would have at each period in the future was then simulated through randomly choosing an example year's return, and calculating the value of ones portfolio at the end of that year. This process was continued for 50 years (the long run). The relative annual wealth changes each period were multiplied

together to calculate the terminal period wealth (relative wealth in year 50). The internal rate of return for the 50 year period was then calculated as:

$$(W_{50})^{1/50} - 1$$

where W_{50} = relative wealth at year 50. Relative wealth at year 1 is one.

This simulation calculates a single long run rate of return for each portfolio. To generate the long run return distribution for each portfolio, this process was run 500 times. For each portfolio, 500 long run internal rates of return were calculated. The mean internal rate of return and its standard deviation were calculated and the results are plotted on figure 2, along with the standard single period risk efficient frontier. Figure 2 shows how the long term risk is much lower than the single period risk. To emphasize the comparison of long run to single period expected rate of return, figure 3 plots these two curves again, but both are plotted over single period standard deviation. Figure 3 graphically shows that the most risky portfolio, that is the one with the highest return and highest risk in the short run, remains the riskiest portfolio, but its long run return is lower than some less risky portfolios and is in that sense dominated. The turn down (increasing risk with decreasing return) occurs at the point where the single period standard deviation equals 16.5 percent. Because timber investments of the kind envisioned in this paper (management of fully regulated forests) are of a long term nature, it seems wise to consider only investments that are non-dominated in the long run, that is portfolios with a short run standard deviation of 16.5 percent or less. If timber investors expect to hold timber investments over the long term, then emphasis should be on the long run rather than single period risk-return trade-offs.

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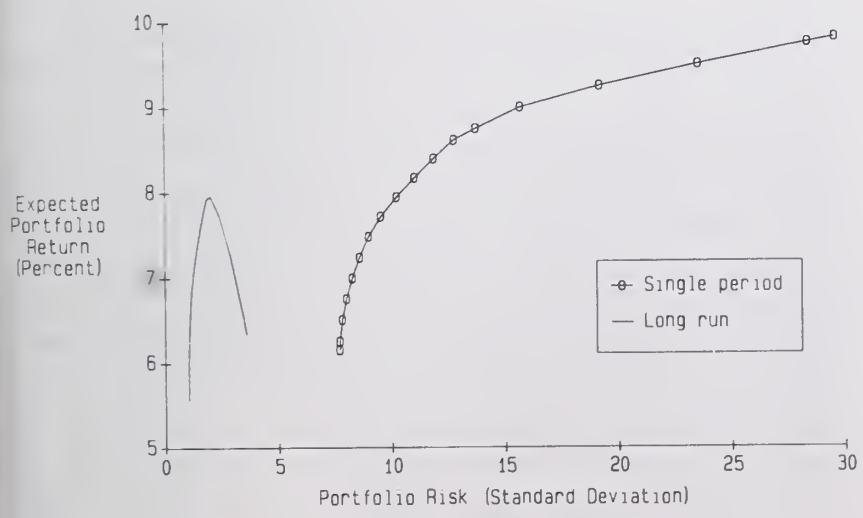


Figure 2.-- Expected portfolio return (percent) versus portfolio risk (standard deviation) for the standard analysis (single period), and long run analysis (long run).

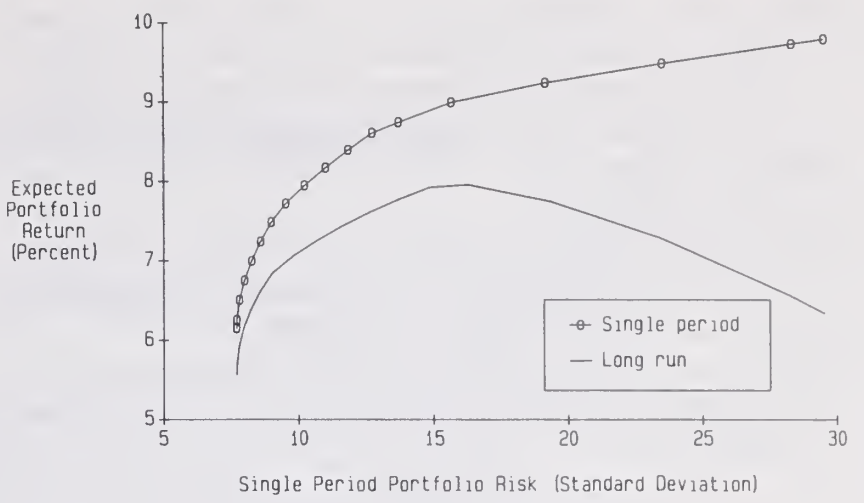


Figure 3.-- Expected portfolio return (percent) versus single period portfolio risk (standard deviation) for the standard analysis (single periods), and long run analysis (long run).

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Area Based Forest Planning

William J. Connelly[1]

Abstract.--This paper proposes an alternative framework for National Forest Planning, analysis, and program implementation. A more systematic approach based on area specific data and analyses is presented in contrast to the current reliance on Forestwide linear programming models.

At present National Forest planning and program implementation are being managed as two separate processes. While a need for integrating Forest planning with project planning is recognized, there are few procedures in place to achieve this. Further, there has been limited attention to completing the cycle of Forest planning, where Forest Plans are both implemented and reevaluated at the Field level.

One possible solution to this problem is Area Based Forest Planning, where implementation of Forest Plans is evaluated for particular areas. This area evaluation serves both to identify projects for implementing Forest Plans and to provide new options for future Forest Plans. This type of Planning would involve simpler analysis models, but wider use of analytical tools at both the Forest and District level. While Area Based Forest Planning in this paper is directed towards National Forests, it would also be applicable to other public and private forest land managers.

The Planning Problem

Although there has always been a certain degree of Forest Planning prior to the passage of the National Forest Management Act (NFMA) of 1976, planning was usually either programmatic (timber sale planning) or area specific (planning for the development of a downhill ski resort). Both of these actions can be classified as "Incremental Planning" (Lindbloom 1965). Generally, "Incremental Planning" focuses on small changes in land management where a particular need arises. In the case of timber sale planning, the increment being considered is whether or not to prepare a timber sale for a particular sale planning area. The increment for the ski area is whether or not to prepare for development, and if so of what nature. The benefit of incremental planning is an effort focused on the particular decision being considered. The drawback is limited consideration of issues or resources beyond the immediate scope of the decision itself.

With the passage of NFMA, National Forest Planning made a significant change in the major thrust of its planning. In order to develop a true multiple resource management plan, the reliance on incremental decisions was abandoned for the more predominant "rational comprehensive" planning model. With this model, the Land Management Plans prepared by each National Forest would derive from a series of integrated land and resource management alternatives for the entire forest. By weighing the different management options presented in these alternatives along with public comment, the Regional Forester is able to identify the single alternative that best "maximizes net public benefits in an environmentally sound manner." The final land management plan would contain detailed standards and guidelines for the implementation of the selected alternative.

While the comprehensive Forest Plan presents a detailed structure for managing a National Forest, it is not detailed or focused enough to provide very specific implementation direction for either particular areas or particular programs. Exceptions to its direction are inevitable. If it does provide very specific direction, it runs the risk of being resisted by Field personnel who have had limited involvement in its development. There is a fear that detailed plan direction will be used in the future by appellants to obstruct particular Forest projects, including those which are in the "spirit" of the plan. A related problem is that while the Forest Plans are being developed, incremental planning has been continuous; sometimes making decisions which compromise alternatives under consideration in the comprehensive plan. When a final plan is finally established, a difficult transition period is likely to occur. Its difficulty is probably proportional to the severity of changes from current direction and the amount of detailed standards and guidelines in the Plan.

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Even though the Forest Service is now clearly committed to both comprehensive and incremental or project planning, the capability and commitment to properly integrate the two has not been realized. This is most vividly demonstrated by the present nature of Forest Planning organizations. Most Planning organizations are located solely at the Supervisor's Office with their efforts focused on the comprehensive plan. There is little or no planning organization at the District level where most of the project planning takes place. Nationally, funding for Planning and Information Management is not recognized in budget line items approved by Congress; Planning either "begs" or "steals" from other functional areas for funding. There is a separation not only in philosophy, but in the organization itself between comprehensive and incremental planning.

The Modeling Problem

The current planning effort centers around the required comprehensive planning model: FORPLAN (Johnson 1986, Johnson et al. 1986) for this round of planning. FORPLAN's structure essentially focuses on timber management options with their resulting environmental and economic consequences on a single acre of land. When dealing with more than one acre of land under the same timber management options; simply multiply by the number of acres under the same treatment. The combination of these management options called "prescriptions" matched with units of land of similar responsiveness called "analysis areas" forms the linear programming problem to be solved by FORPLAN.

Other resource considerations and management activities can be represented in the FORPLAN model if their production functions or work needs can be represented in an appropriate per acre structure. Of course, this results in an expansion of model size by further delineating analysis areas, expanding the prescription set, and increasing the number of constraints. Prescriptions which blend timber management with other resource objectives further expand model size by increasing the number of timing choices. This tends to discourage the development of such multi-resource prescriptions.

The other significant problem in FORPLAN's structure has been frequently called the spatial problem. Until recently, FORPLAN was unable to recognize spatial relationships between adjacent areas of land. This left an analyst with limited options if spatial relationships were important in the model structure. The analyst could use an analysis area parameter to distinguish spatial units, further subdividing the analysis areas and increasing model complexity. To deal with this problem, "aggregate emphasis" (Version 1 FORPLAN) or "coordinated allocation zones" (Version 2 FORPLAN) were provided to represent integrated management choices on particular spatial units. While the analyst could define such choices, he had a limited ability to control the activity and output schedule of the choice. These area capabilities do not replace the normal per acre relationships, but, rather, are an additional structure to it.

Contrary to the structure of FORPLAN and most other per acre timber harvest scheduling models, most production relationships of the Forest are not per acre based. Recreation use is most certainly not related to acreage, or even acreage of particular R.O.S. (Recreation Opportunity Spectrum) classes. The dominant modeling technique for recreation has focused on providing for a certain capacity of recreation classes, presented as a per acre carrying capacity. If there is sufficient total capacity in that class, there is no recreation problem, regardless of whether or not the area has any qualities which would make recreationists want to recreate there. The per acre formulation of FORPLAN leads to a largely irrelevant analysis regarding recreation demands and supply.

Similarly, wildlife problems require consideration of spatial relationships due to the inherent territoriality of wildlife itself. Big game habitat involves a subtle interaction between forage and cover relationships. While both forage and cover can be modeled on a per acre basis, the interrelationship of the two components together can only be achieved through the use of constraints. Other wildlife habitat requirements often depend on a mixture of habitat being present in particular locations. Most of the focus on maintaining viable populations of wildlife species has shifted away from the amount of habitat, as represented in acres, to the distribution of those habitats and other disturbances within the range of a species. Constraints are used in Forplan to try to control these relationships, but there are not enough to manage the spatial considerations of wildlife and also meet all other objectives. Even with constraints, FORPLAN models will always seek the solution which best fulfills its objective function, often leading to an unintended solution for the wildlife problem.

One final example are transportation problems. There are few analysts who have not struggled to represent roading problems with FORPLAN, only to discover that there is no appropriate way to properly integrate roading activity schedules with timber harvest schedules on a forestwide basis. Network problems, such as roading, traffic management, or sediment loads, require a reasonably site specific analysis in order to relate the activity on the network to ongoing activity in related spatial units. Other models such as IRPM (Kirby et al. 1980), Transhipment (Kirby et al. 1981), and recent enhancements to FORPLAN version 2 deal with such network problems on a local area basis, but cannot address an entire forest.

At the Field level, there are a variety of computer aids and a few models such as IRPM or FORPLAN being used with increasing frequency for incremental planning problems at the District level. Geographic Information Systems (GIS) to the extent that they are available, maintained, and used are usually the first reference in preparing project level plans. A variety of new tools are being considered at the District level. These tools can serve both as an aid to project planning, and as a source of information for monitoring and evaluating the Forest Plan. Increasingly, there is discussion and implementation of area planning concepts at the District Level. This is often matched by

a concern about creating another level of planning, with an expectation of "Area Plans" being tied up in the same kind of problems which have affected Forest Plans.

Area Based Forest Planning

Whether a Forest Plan has provided detailed direction for a particular sub-area of the Forest or not, the need is being increasingly recognized for an additional level of comprehensive planning below the Forest level. The primary impetus for this probably comes from Engineering organizations which have found that the Forplan model and Forest Plans do not provide significant assistance in solving their problems and may instead compound their problems by providing inappropriate information. But many other functional areas are also realizing that adequate achievement of their objectives will depend on another level of comprehensive planning. Incremental project planning without some additional comprehensive considerations will be inadequate.

On other hand, Area Planning which proceeds in the same basic environment as project planning may resolve a few problems for a particular area, but does not provide adequate feedback into the Forest Planning process. Area planning, no matter how detailed, may count for little in either this or future rounds of Forest planning, if there are no mechanisms in place to integrate the data developed from area plans into both current and future Forest Plans. Let's examine how Area Planning and Forest Planning could work together to achieve both comprehensive and incremental planning objectives.

Area Determination

Obviously, the first step will be to define Planning Areas. This initial definition can be a serious problem and deserves careful consideration at both the Forest and District level. The most important aspect of area definition is that the areas be large enough to address a number of the cumulative issues affecting an area, yet not so large as to be unable to recognize individual spatial activity decisions (i.e,. harvest units, specific roads, specific trails, specific winter range forage and cover areas, specific range allotments, etc.). It would also be desirable to create an area structure related to the structure of the Forest Plan. While functional areas are likely to conflict over the parameters to use in area definition, the parameters are not that important, as long as the area boundaries are not used as boundaries to the analysis. In order to maintain linkage to other area analyses and forest level planning, it is essential that the areas be fixed for the planning period covered by the Forest Plan.

Inventories

Once areas have been defined and an analysis of a particular area begins, the first step is usually the collection of inventory information. Most of this information can be provided by data in a GIS system. The success and efficiency of this first step in the analysis will depend on how well the GIS and other related data is maintained. In addition, some Field study of the Area will also be required to identify new information and verify GIS data.

From this initial inventory phase, a considerable amount of information should be assembled. With an efficient GIS, multiple map overlays and statistical information can be produced to create a clearer picture of Area. The inventory phase should produce site specific information on such questions as vegetative character of the land, soil conditions, mineral availability, the condition of timber stands, range forage, wildlife populations, unique wildlife habitats, the condition of watersheds and riparian habitat, and special features from a recreational standpoint. In addition, existing uses would also be recognized such as range allotments, mining activity, timber and silvicultural activity, roads, trails, and campgrounds. The inventory should be comprehensive, even if it must be superficial in some areas.

Scoping

The relative emphasis on a particular aspects of the inventory will probably be proportional its importance in the area's management. Each area analysis will also need to establish priorities for itself and its eventual decision making. This process has been called "scoping." It would involve reviewing the current plan direction, identifying new and emerging issues, meeting minimum legal and policy requirements, recognizing interrelated commitments or problems with adjacent areas or ownerships, and identifying other special problems. In some cases, overlapping problems may suggest enlarging the area to be analyzed, by focusing on two areas where an interrelated action is being contemplated. This scoping may or may not involve public involvement. It is important that future new management opportunities be identified, even if they conflict with current plan direction, current use of the area, or even minimum legal requirements.

Alternative Development

From the scoping process, a variety of management opportunities for the area can be developed. These opportunities can be organized into alternative management programs for the areas. Two basic kinds of alternatives need to be developed in the process in order to not only manage the area for the plan period, but also to identify area management opportunities for the future.

The broader type of alternative is the "planning alternative." Each of these alternatives has a set of specific objectives and activity schedules for an area. Each presents a different mix of activities, outputs, and environmental effects as a result of the land management objectives and activity schedule. These alternatives include activity schedules beyond the plan period with

a reasonably detailed estimation of the environmental consequences and activity costs in outyear periods. These "planning alternatives" should not be bound by current management direction for the area. It is important to develop a large number of alternatives, each with a slightly different mix of objectives and schedules. An inadequate set of alternatives will limit the future opportunity of the forest to develop efficient or issue responsive alternatives in the Forest Planning phase.

The other type of alternative is the "action alternative." The "action alternative" is focused on identifying a series of management objectives and activities for the plan period. The focus of "action alternatives" would be on plan period actions and objectives such as which acres to harvest, what roads should be built, what recreation opportunities should be provided, and what areas should be managed for snag habitat, big game cover, or big game forage. As such the "action alternative" must meet minimum legal requirements, be consistent with Plan direction for the Area, and recognize current uses of the land. These alternatives are focused on implementation actions in order to achieve current management objectives.

Both types of alternatives are linked together as each depends on the other. In order to define the actions for the planning period, there will also need to be an identification of likely future consequences and the management options which will remain for the future. These options or "planning alternatives" for an area will only be useful in future planning, if the option for their implementation is not foreclosed by actions taken in the planning period. The process of developing these alternatives would probably occur concurrently, with feedbacks between the two types of alternatives clarifying both the proposed actions in the plan period, and the alternatives which would remain for the future.

Area Analysis

While the objectives are being identified, a related task will be to provide a structure for the analysis of the alternatives. Once again, the analysis must be comprehensive, even if the resources available to do the analysis lead to a superficial analysis in some areas. The scoping process as well as direction from Forest Planning Teams should assist in identifying the aspects of the analysis needing the most effort.

At this point, the detailed and site specific information gathered in the inventory can be evaluated. Computer models can be used to assist in this analysis and also to assist in the generation of alternatives. While use of a single integrated model may be an efficient way to accomplish this in some situations, it may not be appropriate in others. In some cases, there may not be a need for computer models at all. To develop information and alternative schedules for timber harvest, site specific timber and engineering models could be used. For information on recreation opportunities, other models or an non-modeled analysis can be used. For wildlife, there can be some use of timber scheduling models or use of wildlife habitat capability and dispersion models. Whether single or multiple models are used with pre or post-processors does not matter. What is important is that each model uses the same information about the area and its alternatives.

Since the purpose of computer analysis is to analyze the consequences of an alternative, there is no need to force the construction of a perfectly efficient alternative, only feasible alternatives (for "action alternatives") or possible alternatives (for "planning alternatives"). Indeed, the entire economic analysis could be done outside of computer models by attaching a schedule of costs and benefits to each alternative. This kind of economic analysis can consider efficiencies such as reduced administrative costs and economies of scale which cannot be considered in "per acre" type models. It can also focus in on individual sale packages to identify "below-cost sales."

Products of the Area Analysis

The key short term product of the analysis is the selection of the "action alternative." To date, reaching this "action" decision has been the focus of most Area Planning. This decision would include a more detailed identification of site specific management objectives consistent with the Forest Plan. A site specific schedule of proposed management activities such as timber sales, road construction, recreation investments, silvicultural activities, range management, etc., would also be part of "action" decision. A related component would be an identification of the environmental consequences and options remaining for the future which result from the "Action" decision. These would derive from "planning alternatives" consistent with the "Action" decision. This information can be used in NEPA documents to support the actions identified for implementation in the plan period.

The bridge to Forest Planning can be served by retaining the information on the "planning alternatives" which are not foreclosed by the "action" decision. These alternatives can be stored in a computer and narrative format to serve as building blocks for the development of the next Forest Plan. In addition, the analysis and the "planning alternatives" provide a wealth of information about the area itself. This information would include not only the improved data in GIS, but also written information about the area's character and options for future management. This could be valuable to future managers of the area.

Relationship to Forest Planning

Under ideal circumstances, each area of the Forest would have some kind of an Area analysis done to provide "planning alternatives" for the future. Since these alternatives were developed by the Field, there are presumably implementable and would reflect the best information available at the time. In the next Forest Planning process, Forestwide objectives would be

developed for a new set of alternatives. To meet these objectives one "planning alternative" would be selected for each identified Area of the Forest.

Obviously, achievement of this ideal would require a reasonably consistent level of information from each Area (thus the need for comprehensive inventories and analysis, even if superficial), an adequate range of "planning alternatives" from each Area (to provide a wide range of Forest alternatives and meet such objectives as nondeclining flow), careful coordination of Area Planning processes at both the District and Forest level, and a Forest commitment supported Regionally and Nationally to produce a number of these Area Plans in a time frame that permits their use in Forest Planning. The Forest Planning team role has to be one of active managers and a source of technical support to Districts in this Area Planning process.

The more Forest Planning teams develop manuals or "cookbooks" on how to do Area Planning and provide some team leadership and technical support, the easier it will be to focus on the substantive parts of the planning process. Where resources or concern for a particular part of the analysis is limited, data from the Forest Plan may be used in Area Planning. These efforts can prevent each Area planning effort from having to "reinvent the wheel" while ensuring that Area Planning is done in a coordinated and efficient manner.

It may not be possible to get a complete set of "planning alternatives" for each Area identified on the Forest. Some aspects of "planning alternatives" will need to be reviewed to insure that they meet certain "state-of-the-art" technical standards for Forest Planning. In either case, Forest Planning Teams may need to spend some time either developing or refining the alternatives for certain specific areas.

Where commitment to Area Based Forest Planning is lacking, there still remains a capability to use the information from completed area analyses, as long as they were developed with an objective of providing meaningful input to the Forest Plan. This has already happened to some extent in many Forests, where management of certain areas has been determined by planning processes at the District level. However, an organization that continues to prepare its incremental actions with varying planning area boundaries in a non-comprehensive manner will find it difficult to use information developed from incremental analyses in future Forest Planning. In this case, the next round of comprehensive Forest Planning will proceed separately from the incremental planning work which has already been done.

Despite some of the difficulties in achieving the ideal relationship between Area and Forest Planning, a significant effort is likely to yield considerable benefits. These would include a better understanding of planning at all levels of the organization. Greater ownership in the Planning process will result in increased internal and external credibility for both Forest Plans and Area Plans. The wider participation in the planning process will provide opportunities for new ideas in Forest planning and implementation. It will also allow the public an opportunity to understand and participate in Planning on an area specific level as well as the Forest level.

Modeling Area Based Forest Planning

In the past decade most National Forests have gone from a status of having limited computer access to only large mainframe computer systems to a nearly complete reliance on an interconnected computer network. The future promises increased use of microcomputers and better use of GIS systems. As the reliance on computers within the organization has increased, so has the need to develop computer systems which communicate with each other and can exchange information between computers and levels of the organization.

Area Based Forest Planning would need to meet these same realities if it is to succeed as the principal method of planning Forest Service activities and land management. As indicated before there need not be a requirement that all area analyses use the same computer models. However, each area analysis would need to be able to produce similar products and provide for computer storage of information in a consistent format, even if the analyses were developed with different models. Within this framework, each functional area in Forest management should be able to use the appropriate computer tools needed to analyze the effects of each alternative under consideration. Where computers are used to assist in the generation or identification of alternatives, interdisciplinary involvement would be necessary.

Forests may prefer to establish procedures for the use of consistent models for certain types of area problems. The benefits of using consistent models would be increased technical support at the Forest, Regional, or National level; greater ease in assimilating area analyses into Forest analyses; and greater efficiency in completing area analysis. These advantages would have to be weighed against the prospect of committing to a model which may prove too restrictive, inefficient, or inappropriate for a wide range of area analyses.

One approach previously suggested (Connelly 1986) would be to use a family of interrelated FORPLAN models in this manner. Area analyses could use network equipped FORPLAN in an interdisciplinary environment to develop a set of planning and action alternatives for each area. The Area FORPLAN models would be used primarily for identifying timber schedules and accompanying road construction to meet various objectives. Other resources such as wildlife, recreation, and range would be involved in the design of objectives for the FORPLAN model, and could use either FORPLAN or other models to analyze the effects of the alternatives. The FORPLAN developed information along with additional information on each alternative developed outside of FORPLAN could be collapsed into a single column in a Forestwide model. Conversely, Forestwide models could be stripped down to assist area analysis. Models could be linked in a single system.

At the Forest level, each of the "planning alternatives" developed for each Area would be represented as a single column in a Forest matrix linear programming problem. Thus each Area develops a set of alternatives as follows:

AREA 1 AREA 2 ...AREA n

$\{PA_{1,1}, PA_{1,2},..PA_{1,m1}\}$ $\{PA_{2,1},..PA_{2,m2}\}$ $...\{PA_{n,1},..PA_{n,mn}\}$

where each $PA_{n,mn}$ represents a "planning alternative" variable with all of its associated activities and outputs. This includes narrative or other information not involved in the linear programming model. There are $_{n}$ areas represented each with its own $_{mn}$ number of alternatives. Permissible values for each PA variable would range between 0 and 1. Representing this structure into a sample matrix would produce the following types of equations:

Area Control for Area 1

$$1PA_{1,1} + 1PA_{1,2} + ..1PA_{1,m1} + 0PA_{2,1}, \quad +$$
$$..0PA2_{,m2} + ..0PA_{n,1} + ..0PA_{n,mn} \quad = \quad 1$$

Timber Volume per decade (coefficients represent MMCF per decade)

$$4.3PA_{1,1} + 3.3PA_{1,2} + ..0PA_{1,m1} + 10PA_{2,1} \quad +$$
$$..1PA_{2,m2} + ...3.2PA_{n,1} + ..0PA_{n,mn} \quad <>=MMCF_1$$

$$4.3PA_{1,1} + 3.0PA_{1,2} + ..1PA_{1,m1} + 5PA_{2,1} \quad +$$
$$..2PA_{2,m2} + ...3.2PA_{n,1} + ..0PA_{n,mn} \quad <>=MMCF_2$$

Thus alternative $PA_{1,1}$ represents a nondeclining flow schedule, alternative $PA_{1,2}$ represents a small departure, and $PA_{1,m1}$ represents a deferred harvest schedule for Area 1.

Old Growth per decade (coefficients represent Thousand Acres of old growth)

$$2.5PA_{1,1} + 4.0PA_{1,2} + ..8PA_{1,m1} + 4PA_{2,1} \quad +$$
$$..16PA_{2,m2} + ...10PA_{n,1} + ..12PA_{n,mn} \quad <>=MAcres_1$$

$$2.0PA_{1,1} + 3.3PA_{1,2} + ..7.8PA_{1,m1} + 1PA_{2,1} \quad +$$
$$.15PA_{2,m2} + ...9PA_{n,1} + ..12PA_{n,mn} \quad <>=MAcres_2$$

Thus Area 2 is shown to be a larger area in terms of old growth than Area 1, and the two alternatives shown for Area 2 are far more different from each other than the alternatives presented for Area 1.

PNV over the Planning Horizon (Millions of Dollars)

$$.65PA_{1,1} + .80PA_{1,2} + .. .15PA_{1,m1} + 1.1PA_{2,1} \quad +$$
$$.. .5PA_{2,m2} + ...5PA_{n,1} + .. .2PA_{n,mn} \quad =PNV$$

Alternative $PA_{1,1}$ is shown to be a less efficient alternative than $PA_{1,2}$, despite its harvest of more volume in the first decade.

Additional special rows and columns may be added to the matrix for cumulative

Forest and temporal relationships such as nondeclining flow or departure bounds, multi-area traffic control, or the flow of forage for big game or livestock over time. Obviously, in seeking either 0 or 1 solutions for each variable representing a "planning alternative," a linear programming solution may produce fractions between 0 and 1. A variety of mechanisms may be used to resolve this problem, including beginning with a review of the solution to determine why the fractional values occurred. Since the solution being sought to the Forestwide problem involves a combination of one alternative for each area, these combinations may be tested against all of the various Forestwide objectives until an appropriate, but not necessarily optimal, combination is identified. An algorithm added to the linear program package could facilitate this testing.

It is likely that the principal objection to this approach to Forest modeling would be that an inadequate range of timber harvest schedules and intensities is being considered, thus leading to a loss of overall Forest timber production. This objection ignores the fact that optimization on a very large set of harvest schedules with per acre models may produce more timber volume in model solutions than can actually be implemented on the ground. However, collapsing timber schedules on an area basis will require that a considerable range of implementable harvest schedules be developed for each area. Unlike per acre models, these schedules would have been assessed by the Field and identified as potentially implementable. Another consideration is that the addition of site specificity may enable better representation of Timber yields for a Forest, possibly resulting in even higher timber levels than yields developed over broadly averaged Forest strata.

Conclusion

This paper has emphasized the advantages of using area planning for three principal purposes: (1) as a basis for developing individual projects to implement an existing Forest Plan, (2) to provide a record of detailed area information including identified future management options, and (3) to provide area specific alternatives for future Forest Plans. This does not mean that there might not be some disadvantages. Planning and data management activities would need explicit recognition as an independent and vital part of the National Forest management. People and dollars would be needed to support such a concept. Careful control of the entire planning process would become a priority mission for the Forest Service.

From my point of view, moving to Area Planning is inevitable in the long run. When I contemplate the value of such a planning process versus any increased costs, I'm sure that this would represent more efficient Forest management. The magnitude of any increased costs can also be controlled through better coordination and reduced duplication of Planning effort. More efficient use of GIS and other computer capabilities promises to make initial data gathering much simpler than it has been in the past. The Forest Service is already headed in this direction; the question is whether or not it will seize the initiative for this future.

Prior to the passage of NEPA and NFMA, the National Forests were incrementally managed to meet identified targets and programs. Planning could focus on just management of a single program or a single incremental decision. Multiple use management, although understood as part of the agency's mission, did not require as much in terms of planning since the Forests had a capability to meet nearly all of society's demands for Forest resources.

The passage of RPA-NFMA heralded the end of that period and the beginning of a new period of comprehensive Forest planning to meet multiple use objectives. These acts recognized that demand for Forest resources were beginning to exceed supplies. Comprehensive management plans would be needed to balance the conflicting uses of the land. The initial round of Forest Planning has sought to meet these multiple uses primarily through a zoning model of land allocation to emphasize a particular use. There are some who feel that it is inevitable that National Forest management will break down into separate areas managed primarily for single use purposes. Area planning and Area Based Forest Planning would require consideration and some integration of multiple use planning objectives in the management of each area. As such it represents the best opportunity the Forest Service has to demonstrate that multiple use management on all Forest lands can better serve our nation's needs than segregated single use management.

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Using Priced and Unpriced Values to Make Environmental Decisions

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Abstract.--A process is described for making comparative valuations of a wide range of environmental management activities when the combined social, economic, managerial, and political benefits of some (but not all) of these activities cannot be adequately described in economic terms, and budgetary constraints do not permit funding all activities under consideration. The process accounts for subjective judgment and contains a formal rigorous decision strategy that takes the place of intuition when quantitative and qualitative values of environmental activities need to be evaluated.

The qualities that make a good manager come down to decisiveness. "You can use the fanciest computers in the world and you can gather all the charts and numbers, but in the end you have to bring all your information together, set up a time table, and act" (Iacocca 1984). The decision process described in this paper is intended to assist managers of natural environments in taking that action.

In many ways the quality and quantity of natural environments in the year 2000 and beyond are being determined and shaped by today's long-range planning activities and priorities. Yet, the expected benefits that may emerge from some of these activities can only be speculative at best. To be effective, long-range planning and priority-setting efforts must account for subjective judgment and contain formal, rigorous decision strategies that replace intuition (McCormack 1984, Peters and Austin 1985).

This paper describes a method to set priorities among a wide range of environmental management activities by using subjectively derived benefit scores and projected costs. The method was used initially in a variety of priority exercises in USDA Forest Service research but has also been applied by executives, negotiators, policymakers, analysts, and others who need to make decisions under uncertainty and risk when the dollar value of the benefits are unknown (Davis 1987; Davis and Schaffer 1984; Schaffer et al. 1977; National Agricultural Advisory Research and Extension Users Advisory Board 1983, 1984; USDA Forest Service 1983). The basic premise in the process is that human judgment is indispensable to decisionmaking in long-range planning (Harris 1964, Shelly and Ryan 1964).

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The Problem Of Setting Priorities

In any organization, budgetary constraints do not permit funding all the actions or initiatives the organization wishes to pursue. Inevitably, managers are forced to set priorities on what they do, and frequently priorities must be set on some projects or efforts that cannot be evaluated through conventional economic benefit-cost analysis.

For example, suppose a forest manager has to choose between concentrating limited financial resources on (1) an effort to increase saw timber volume production or (2) increase opportunities for nonmotorized, dispersed recreation opportunities in remote scenic areas. Economists can make a benefit-cost analysis of the benefits to be derived from the timber production, but the social benefits associated with an effort to enhance access to scenic quality are not easy, and sometimes impossible, to describe in economic terms. The problem is how to decide, given limited budgets, whether to invest in timber production or access to scenic quality.

The decision theory literature is filled with examples, some much more complex than the one just described, of how executives, when faced with a difficult, complex decision, traditionally gather information or appoint a committee to do it, or both (Austin 1966, Kahn et al. 1964, Richards and Greenlaw 1972). As a result, an executive may be overwhelmed with

difficult to evaluate data, or become mired in trade-off considerations as proponents push favorite programs. When decisions are made, it may be difficult to discover why the choice was made. There is no "audit trail."

A Design For Making Decisive Decisions

The design described below does not make decisions and it does not portend what to decide. Rather, it helps facilitate consensus and defines priorities by using coherent decisions consistent with stated values of the decisionmakers themselves.

The design involves seven steps:

1. List items to be evaluated.
2. Select a panel of objective evaluators.
3. Survey the panel to evaluate the items in terms of their overall benefits.
4. Compute benefit scores.
5. Estimate the costs.
6. Compare initial benefit scores and costs.
7. Adjust benefit scores to reflect management's values and beliefs.

Each step is now described using a hypothetical example of a forest manager who must make tradeoffs between environmental quality and the production of goods and services from the forest land under his direction. The same methods could be applied also to such diverse problems as selecting the "best" location of a new electric transmission line or deciding which of several alternative methods that should be used in solid waste disposal.

List the Items

Suppose a forest manager needs to arrange the following 10 management activities, A through J, in order of priority, based on the overall benefits and estimated costs for each.

A. Increase saw timber volume production.

B. Initiate water yield improvement measures.

C. Increase scenic highway development.

D. Increase nonmotorized, dispersed recreation opportunities.

E. Develop a project for range grazing use improvement.

F. Increase the opportunities for developed recreation.

G. Improve wildlife habitat areas.

H. Improve fish habitat including spawning areas.

I. Reclaim areas adversely impacted in past mining operations.

J. Increase and improve winter sports and ski area development.

The manager estimates the total cost of all of the projects to be 250,000 dollars but only has a current operating budget of 150,000 dollars. The manager decides that each activity is independent of any other and that it will be more effective to complete as many projects as possible, rather than use a "piecemeal" approach in which several will be partly completed.

The words used to describe the 10 efforts (A through J) are typical statements involved in priority setting. For example, members of the National Agricultural Research and Extension Users Advisory Board (1984) used these kinds of broad, general descriptions of research (or management) efforts within the decision design described here--when recommending program priorities to Congress. At other management levels, the activities may need to be described more specifically. The question of "how specific" is a difficult one for two reasons. First, the number of alternative investment strategies available to the decisionmaker, even in the hypothetical example used here, may be extensive. Heterogeneous information bears on each investment strategy. Second, the decisionmaker is faced with imperfect knowledge about the expected costs of each activity, as well as considerable uncertainty about their benefits that may be difficult (in many cases impossible) to specify in a totally objective way. Many times total benefits of a given activity cannot be described very well even by the manager(s) most intimately involved with the program prioritization or selection (USDA Forest Service 1981). Nonetheless, the programs and their expected results should be described in the context of the combined political, social, economic, managerial, and environmental values of each one. The degree of generality or specificity of the description of each management activity is kept as uniform or as parallel as possible. This is not easy--especially if there are a large number of activities to be evaluated and prioritized.

In addition, the expected results from management activities within each of the 10 activities must be described. For example, some of the potential results under project F--Increase nonmotorized, dispersed recreation opportunities might be:

> Physical experience--the opportunity for physical exercise and exertion that stimulates the body.
>
> Emotional experience--the thrill of experiencing new sensations and exploring wild regions--experiences that deal with an achievement of some sort.
>
> Aesthetic experiences--the enjoyment of the beauties and variety of relationships that exist in natural environments.
>
> Educational experiences--the opportunity to gain new knowledge or teach others about the soil, water, wildlife, plant, and other scenic resources.
>
> Social experiences--the chance to engage in conversations ranging from brief casual meetings to more lengthy conversations with companions or during stops at overnight camps (Schaffer and Mietz 1969).

Select a Panel

The second step is to select a panel of knowledgeable people to make judgments about the importance of the items to be evaluated. The number to include on the panel depends on the variation in the subjects to be considered. It is not always easy to separate scientific competence from policy involvement; indeed, that may be partly due to involvement in policy. On the other hand, selecting panelists purely for managerial or scientific competence may give results that are tilted toward one side of a policy debate. Select panelists who are "honest brokers," people who are willing to be objective in judging overall program benefits of the items being evaluated.

Conduct a Survey

Third, panelists are given or mailed a description of the activities (10 in our example), background information such as a list of the results from each activity, and a survey form (table 1). Everyone compares the 10 activities, two at a time, on the bases of overall perceived environmental, social, economic, managerial, and political benefits. Timeliness is an important consideration. Programs whose benefits may only be derived in the distant future usually should not be considered as valuable as a program that will show immediate benefits.

An important limitation on the paired comparison method is the practical limit on how many items can be compared. The equation is:

$$f = \frac{n(n-1)}{2}$$

where "f" is the number of paired comparisons and "n" is the number of things compared. In the hypothetical example, "n" equaled 10; consequently there were 45 comparisons--about as many as one can expect from a panel of busy people.

There are at least three major reasons why a mailed survey is recommended over group discussions. One is cost. Second, fuzzy thinking abounds in initial group discussions of this kind. The desire for solidity among panelists can cloud the initial analysis and thinking necessary to reach a balanced decision (Janis 1983). The third is "band wagon jumping." There is a strong desire for many to agree with others even though they believe or possess information that might lead to a different conclusion.

Methods for estimating the overall value of a large number of diverse items under these circumstances have been developed in a wide range of disciplines--including economics, political science, psychology, and sociology. Despite differences in approach, these methods tend to blend. Pair-wise comparing all items, two at a time, may be used; for example, to derive an attitude scale for a psychologist (Bock and Jones 1968, Edwards 1957, Torgerson 1958) or a utility scale for an economist (Sinden and Worrell 1979). In fact, the various disciplines often use different terms for the same thing. Economists make the most use of these methods as value indicators for making priority decisions.

Compute Benefit Score

Fourth, the benefit scores are computed. The percentage of times all respondents select each activity over every other provides the basic data for computing (Edwards 1957, Ross 1934) the benefit scores (table 2). Note that the benefit scores are normalized (values systematically changed), so that they sum to 1000. The units of "benefit" are not specified--they can be considered as units of utility if one wishes.

Table 1.--Survey forms and hypothetical entries of how one panelist compared all two-way sets of 10 projects.

Items	A Sawtimber production	B Water yield	C Scenic highway	D Dispersed recreation	E Range improvement	F Developed recreation	G Wildlife habitat	H Fish habitat	I Mining & oil	J Ski development
A. Sawtimber production	X	1	1	1	0	1	1	0	1	0
B. Water yield		X	1	1	0	1	1	0	0	0
C. Scenic highway			X	1	0	0	1	0	0	0
D. Dispersed recreation				X	0	0	0	0	0	0
E. Range improvement					X	1	1	1	1	1
F. Developed recreation						X	1	0	0	0
G. Wildlife habitat							X	0	0	0
H. Fish habitat								X	1	0
I. Mining & oil									X	0
J. Ski development										X

A "1" indicates the benefits of the column item judged more favorable than the benefits of the row item. A "0" means just the opposite.

Table 2.--Hypothetical example of how benefit scores were calculated for 10 land management activities.[1,2,3].

Items	A Sawtimber production	B Water yield	C Scenic highway	D Dispersed recreation	E Range Improvement	F Developed recreation	G Wildlife habitat	H Fish habitat	I Mining & oil	J Ski development
--Proportion of times column research effort was judged more favorable than row research effort--										
A. Sawtimber production	.00	.70[1]	.15	.10	.15	.15	.60	.00	.60	.10
B. Water yield	.30[2]	.00	.00	.00	.15	.30	.45	.25	.45	.25
C. Scenic highway	.85	1.00	.00	.30	.60	.70	.60	.25	.60	.30
D. Dispersed recreation	.90	1.00	.70	.00	.85	.70	.75	.55	.75	.85
E. Range improvement	.85	.85	.40	.15	.00	.55	.60	.40	.75	.60
F. Developed recreation	.85	.70	.30	.30	.45	.00	.75	.30	.60	.55
G. Wildlife habitat	.40	.55	.40	.25	.40	.25	.00	.25	.55	.25
H. Fish habitat	1.00	.75	.75	.45	.60	.70	.75	.00	.75	.70
I. Mining & oil	.40	.55	.40	.25	.25	.40	.45	.25	.00	.25
J. Ski development	.90	.75	.70	.15	.40	.45	.75	.30	.75	.00
Totals (Grand Total = 45.00)	6.45	6.85	3.80	1.95	3.85	4.20	5.70	2.55	5.80	3.85
Benefit scores (Total benefit scores = 1000)	143[3]	152	84	43	86	93	127	57	129	86

[1]Let's assume 10 panelists were used in this survey. We add the individual raw scores from the survey forms (for example 1+1+0+1+1+0+1+1+1 = 7) and divide the number of panelists (7/10 = 0.70).

[2]The value in a cell to the left of the diagonal dashed line is: 1.00 minus the corresponding pair-wise comparison value to the right of the diagonal. For example, the 0.30 in the first column, row two, is the result of 1.00-0.70; the 0.70 is being located in the second column, row one.

[3]Benefit scores are normalized so that they sum to 1000; for example, 6.45/45.0 x 1000 = 143. Multiplying by 1000 is a convenience to avoid the use of decimal points in the benefit scores.

Estimate the Costs

Fifth, the annual cost of each activity needs to be estimated. This step should be done concurrently with, and independent of, the panel survey to develop benefit scores. Experienced persons should estimate the costs of each activity being evaluated without being influenced by the values of the benefit scores.

The total cost for each activity is discounted to present worth--the money needed today in order to fund the activity in total. The rate of interest is selected by the manager and based on prevailing discount rates. Only activities with similar timeframes should be compared. A project that will be quickly terminated, or one for which funding will be delayed, usually should not be compared with the others. Since costs are explicitly discounted, it is important that there be an implicit discounting of the benefits also, based on their expected delivery time.

Compared Initial Benefit Scores and Costs

A computer can quickly summarize results of the individual benefit scores provided by each panel member, as well as the costs for the 10 activities (table 3).

Each activity is then ranked and plotted according to benefit scores to form a benefit-only criterion curve. That is, the program with the highest benefit score (in this case B--initiate water yield improvement measures) is plotted first, against its cost. The program with the next highest benefit score (A--saw timber volume production) is plotted second, in a cumulative manner, until all projects are arranged along a curve (fig. 1).

Efforts are also plotted by a cost-benefit criterion. In this case, D (nonmotorized, dispersed recreation opportunities) is plotted first because it has the largest benefit-cost value (table 3), H (fish habitat improvement) is next, etc. (fig. 1).

Table 3.--Initial and final results after fine tuning the benefit scores of the 10 activities.

Research effort	Initial results			Final results	
	Initial benefit score	Discounted cost (millions)	Initial benefit/cost criterion value	Final benefit score	Final benefit/ cost criterion value
B. Water yield	152	16	9.50	216	13.50
A. Sawtimber production	143	36	3.97	123	3.41
I. Mining & oil	129	56	2.30	164	2.93
G. Wildlife habitat	127	9	14.11	110	12.22
F. Developed recreation	93	30	3.10	80	2.67
E. Range improvement	86	20	4.30	74	3.70
J. Ski development	86	35	2.46	74	2.11
C. Scenic highway	84	26	3.23	72	2.77
H. Fish habitat	57	2	28.50	49	24.50
D. Dispersed recreation	43	1	43.00	38	38.00
Totals	1000	231		1000	

The two resulting curves provide a tool that can be used, along with other considerations, for making decisions about the priorities of the activities under various cost constraints. As figure 1 shows, the cost-benefit criterion curve always provides more benefit for a fixed investment. For example, if a program budget is set at 150,000 dollars, a program that contains efforts D, H, G, B, E, A, F, and C--with a total benefit score 800--is preferred, rather than a program with efforts B, A, I, G, and E--with a total benefit score of only 660 (fig. 1).

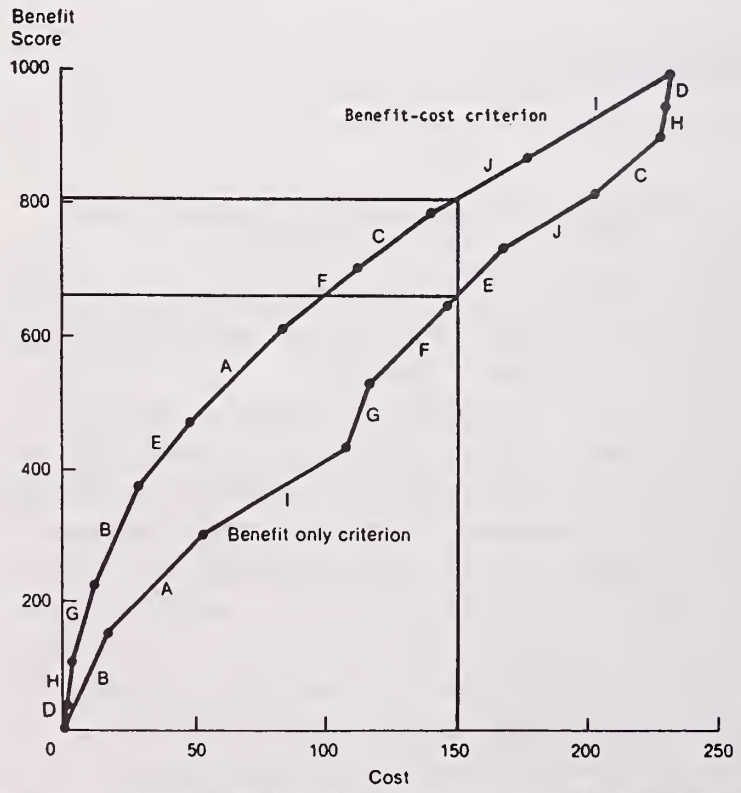


Figure 1.--Cost-benefit versus benefit-only criteria: initial results.

Adjustment by Management

The primary advantage of the decision-analytic approach, up to this point, is that it provides an organizing and clarifying framework for facilitating consensus in complex decisionmaking situations. However, since management is responsible for the final content and success of activities being considered, final decisions on content and benefits of the activities is theirs. Thus, management may wish to adjust the initial benefit scores based on social, political, economic, scientific, or environmental information not evident or important to panel members.

Such adjustment is a systematic method whereby management examines and may change benefit scores (and thus the location) of the activities along the cost-benefit criterion curve (Armstrong 1987). The only constraint is that regardless of the number of changes that are made, the sum of the scores must equal 1000. For example, if management wants to increase the benefit score of one activity, it needs to reduce the value of another, or others, an appropriate amount.

The adjustment process might work like this. Management compares the program package D, H, and G on the cost-benefit criterion curve with B on the benefit-only criterion curve. Both packages cost about the same, but the first has 1 1/2 times the benefit score value as the second. However, management may feel that B is more important than D, H, and G--regardless of what the data suggests (table 3). So, B's benefit score is adjusted--let's say 250. The reason(s) for the change is documented, and the scores of all of the other efforts along the curve are adjusted (that is normalized) so that their sum equals 1000.

Next, management observes that the package D, H, G, B, E, A, and F on the cost-benefit criterion curve have a higher total benefit for the same cost than the package with B, A, and I on the benefit-only criterion curve. Since B and A are common to both packages, and there is no interdependences among the efforts, I can be compared to D, H, G, E, and F. Let's assume management wants I's score changed to 190. The change is made, the data is renormalized, and the adjustment process continues until management is satisfied with the final benefit scores of all activities. Final benefit-cost data are computed (table 3), and a final set of curves are portrayed (fig. 2).

Figure 2 shows the optional order of investment for a dissimilar mix of activities. Note that for any arbitrary limit on cost, the best mix is defined (e.g., if the budget is $150,000, the best investment strategy is D, H, B, G, E, A, and I.

Limitations on the Design

1. The design for decision approximates the value of the items being considered--as perceived by panel members.

2. Results depend on the approximation used to define and specify the design.
3. Those approximations deal with the state-of-knowledge regarding interdependences, costs, benefits, uncertainties, risks, and timeliness of the effort.
4. Approximations are innate to complex problems and should be refined as better information becomes available.
5. Results reflect only the knowledge and judgment of the panel participants.
6. The system will be unfamiliar to most participants. However, when it is understood, it is usually accepted by managers and panelists and should have application to a wide range of environmental decisionmaking.

Advantages of the Design

1. Participants apply judgments to a set of well-designed, content-specific situations.
2. The procedure incorporates anticipated accomplishments; however, whenever this information is incomplete or unavailable, the panelists should use their judgment in keeping with their background and expertise.
3. The rational supporting subjective judgments is elicited and captured. Thus, the approach recognizes that human judgment is indispensable to the problem solution.

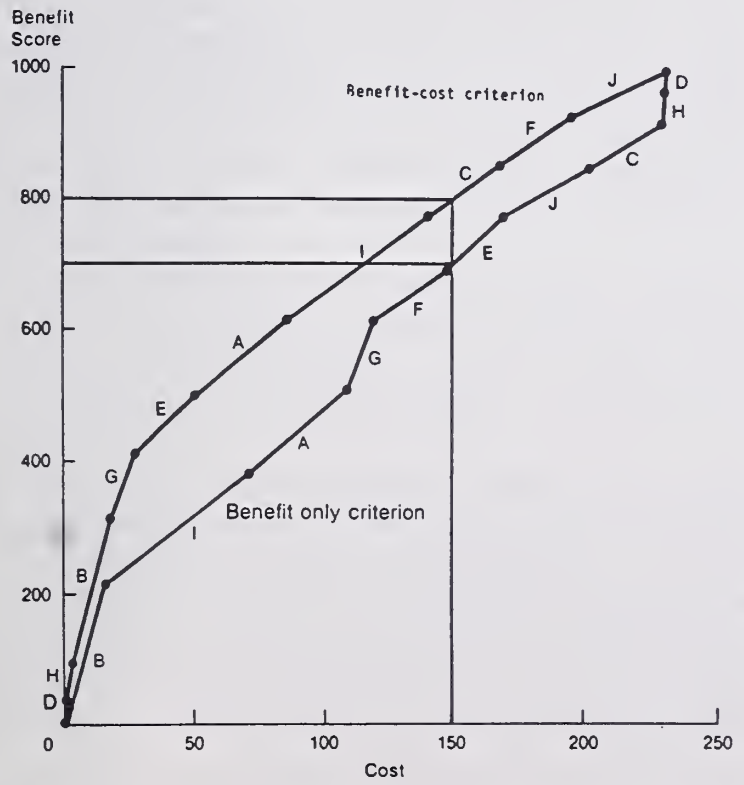


Figure 2.--Benefit-cost versus benefit-only criteria: final comparisons.

4. The system leaves an "audit trail" in which most decisions are made specific, many of them quantified.
5. The approach accommodates selective comparisons and tradeoff of dissimilar items. When comparing different items, panelists must evaluate relative consequences of various mixes of programs, no matter how diverse they might be.
6. Comparison through rational, informed, subjective judgment is an indispensable part of all decisions. The psychology of human choice requires it, and the design for decisions provides a logical foundation for capturing it.
7. The cost-benefit criterion curve is clearly linked to relative benefits with no issues hidden within the procedure.
8. The structure of decisions is visible and invites investigation, discovery, and constructive criticism. It facilitates challenge, sensitivity analysis, and improvement through debate.
9. Results can be used to gauge impacts of budget constraints and modifications.
10. This decisionmaking procedure under uncertainty can serve as the hub of an information system for overall program investment strategies. In turn, these strategies influence and promote decisive decisions that concern the social, economic, environmental, and practical realities of the environment.

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Stand Level Sensitivity Analysis on the Effect of Markets on Optimal Management Regimes

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Abstract.--This is a report on sensitivity of optimal loblolly pine stand management in relation to stumpage market price functions, stand quality, and merchandising criteria. Oriented strand board, high speed sawmills (scragg type mills), and a combination of the two are the three stumpage markets. When size and quality are important for a stumpage market manufacturing process, lower initial planting densities are required; but they must be high enough to maintain wood quality. Also thinning, if any, is precommercial and rotation age is longer. For markets where quality and size have little effect on price, oriented strand board, planting densities are high, rotations are short, and there are no thinnings. For a stumpage market which has both lumber and fiber manufacturing processes, optimal stand management is sensitive to relative manufacturing costs. Optimal management regimes are highly dependent on markets.

Speaking candidly, it is an impossible task to determine optimal stand management regimes. This is said in recognition of an unknown future. The mathematics are simple. It is the information requirements which are impossible. We can do a reasonable job of predicting growth and yield of timber stands. However, we do a relatively poor job of predicting the future for a wide variety of economic, physical, and biological factors including markets, manufacturing technology, interest rates, prices, production costs, risk, timber quality, and nontimber site factors among others.

Where does this leave us? With our knowledge of stand level management, we can make "intelligent" guesses on the state of future factors and we can study how variations in factors affect optimal decisions. This is where sensitivity analysis plays an important roll.

Every timber stand has a unique set of factors which affect optimal management regimes. These factors can be classified as either control variables, those which management can influence, or noncontrol variables over which management has no influence. Several stand management optimization studies have recognized noncontrollable variation in factors, and accordingly, contain a sensitivity analysis of control and noncontrol variables. Noncontrol variables over which sensitivity analysis has been performed include: management objective, stumpage price function, site quality, interest rate, regeneration cost, initial stocking, and risk.

This paper reports on a sensitivity analysis study of stand level management to market type: high speed sawmills, oriented strand board, and a mix of the two. Also included are the impacts of changing petroleum prices, merchandising criteria, and stem quality. Stem quality is defined in terms of differences in limbiness associated with stand density. The North Carolina State University Loblolly Pine Plantation Management Simulator (Hafley and Buford 1985) was used as the basis for the optimization. Nonlinear programming, as reported by Roise (1986), was used to locate optimal points. Thinning strategy was limited throughout to one commercial thinning.

Since tree quality has not been a factor in previous loblolly pine stand management sensitivity, an additional objective of this study was to demonstrate both a rationale for its inclusion in optimization studies and its impact on the location of the optimum. Since southern pine grading rules place a high premium on knot size, limbiness was chosen as a surrogate for grade. In a recent article, Briggs (1987) considered quality in a Douglas fir stand optimization study. Though preliminary in nature his article points out the importance of including quality in growth and yield predictions and optimization studies.

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PRICE FUNCTION SENSITIVITY

Managers are interested in more than single point optima. Rather, they are interested in the whole range of management possibilities and how changes will affect bottom line results. For this reason, we have chosen to report our results as response function maps which encompass the optimal point. This is in recognition that even though optimal stand management is a desirable goal, forest management requires trade offs between activities which, in turn, lead to "suboptimal" combinations of activities. Thus, it is important to understand sensitivity to alternatives.

The control variables in this study are planting density, single thinning time and intensity, and harvest age. The noncontrol variable, over which management sensitivity is examined, is the price function. Three price functions are used. One for an oriented strand board plant (OSB), one for a high speed sawmill (HSS), and one for a merchandised combination of the two (MIX). Appendix A summarizes the three price functions and all assumptions.

As stated earlier, published literature indicates little agreement on the structure, use, and results from different stumpage price functions. This is because a unique price function can be derived for almost every situation. Land owners selling stumpage use market price. An integrated forest products firm may use an internal transfer price. A pulpwood market price may be based on quantity. A veneer-wood market price is based on both quantity and quality. Hotlvedt and Straka (1987) note that stands are commonly evaluated using expected regional average stumpage prices which are discontinuous from one product to another, cyclical and subject to wide geographic variation. Not surprisingly, these prices do not apply to any specific situation. They are appropriate only for regional decisions and could lead to incorrect results when applied to specific or local situations.

What implications do price functions have on stand management decision making? The use of the wrong price function can lead to erroneous decisions when comparing just two stand management regimes and large errors in estimating optimal management regimes. An alternative to average price for stumpage is residual value price. Residual value is gross revenue from sale of end products from a tree minus total cost of converting the tree into the final products. A logical wood product producer will value a tree, as part of a stand, based on internal firm residual values. In a competitive bidding environment, this will be reflected in stumpage price. The more suitable the raw material in a stand is for a bidders manufacturing process, the more that can be paid. Nonetheless, what is paid and what could be paid are two different amounts. Buyers want to maximize and sellers want to minimize the difference between these two amounts. For the buyer, the difference is profit. For the seller the difference is lost profit. Therefore, the use of the wrong price function would lead to an erroneous estimation of profit.

Table 1.-- Range of price functions analyzed. Numbers refer to unique cases. All 1's are the same case, all 2's are the same case, and so on. For the mixed market it is assumed that wood is allocated to the market of highest value. The following statements describe the difference between cases: changes in wax and resin price does not impact wood quality; changes in stand density does not change OSB value; harvesting cost is a function of diameter alone; the cost of competition suppression at low densities is not included; the increased knot and limb size at lower densities only affects wood value in cases 10 and 11.

Case descriptions Price and density factors	Type of market Oriented stand board	 High speed sawmill	 Mixed market
No density adjustments 1985 price of wax and resin	1	2	3 (1+2)
No density adjustments Double 1986 price of wax and resin	4	2	5 (4+2)
No density adjustment Triple 1985 price of wax and resin	6	2	7 (6+2)
Wood from live crown cannot be used as sawtimber 1985 price for wax and resin	1	8	9 (4+8)
Sawtimber value decreasing with planting density 1985 price for wax and resin	1	10	11 (4+10)

Price Functions for Three Markets

This section examines loblolly pine stand management in relation to stumpage price functions. The different price functions examined are listed in table 1. As used here, stumpage price is a function of market, tree quality, and diameter class. Three variations are made to the basic raw wood market types: one deals with an external cost factor, one with merchandising, and the last with quality. The external factor is the cost of wax and resin in the manufacture of OSB. Wax and resin, petrochemicals, are assumed to be linearly related to the cost of crude oil. Harpole (1985) in a comparison of isocyanate and phenol-formaldehyde bonding costs noted that cost per thousand square feet is highly sensitive to changes in wax and resin cost, more so than the cost of wood. The merchandising variation is to disallow wood within the live crown for use as sawtimber. To accomplish this, a function was developed to estimate crown ratio given the stand age and initial spacing (appendix B). Concern for quality is a reason for maintaining "full" stocking. As density decreases, tree size increases but quality decreases. For this reason, we examine effect on optimal management practices to changes in raw wood characteristics caused by stand

density conditions. To accomplish this, the price function was modified such that as the planting density decreased below 400 trees per acre the value of sawtimber decreases linearly, until at a planting density of 100 trees per acre the sawtimber value is zero. Appendix A contains a complete summary of assumptions made in this study.

Timber purchasing competitiveness for alternative forest products manufacturing facilities was analyzed by Deal (1986). This required development of detailed residual stumpage price functions. In addition to OSB and HSS, he estimated price functions for conventional sawmills and medium density fiberboard plants. His HSS wood value is a function of tree diameter and height, while his OSB wood value is constant per unit, except for the effect of harvesting cost (appendix A). These prices represent the maximum amount a mill could be willing to pay for stumpage and still break even. Because of short expected rotation ages, it is assumed that plantation rotations will not produce any trees that grade better than Southern Pine Grade C.[2] Classifying all trees as grade C was suggested by examination of plantation spacing studies. Lumber grade yield was determined for grade C trees using the lumber grade yield method of Schroeder et al. (1968).

As a result, within this study, there are 15 price function combinations: three markets with and without crown merchandising adjustments, three markets with and without quality adjustments, and three markets with three different levels of external price for wax and resin (table 1).

Stand Management Results for Three Markets

Table 1 presents a listing of the combinations of market, merchandising, and external price (Case 1 through Case 11) used in this study. Summarizing the effect of the different cases on loblolly pine plantation management we find that: markets with constant price functions (like OSB) are optimal at high planting densities, no thinning, and short rotations. Markets with diameter sensitive price functions, like HSS, result in low optimal planting densities, no thinning, and longer rotations. However, markets with diameter and quality sensitive price functions result in intermediate optimal planting densities with a precommercial thin and even higher harvest ages. Markets with a mixed (OSB + HSS) price function lead to a wider range of stand management choices. Each market price function leads to a distinct optimal stand management regime. The results reflect trade offs made between three basic raw material characteristics: total stand volume, tree size, and wood quality. Optimal stand management is an attempt to equate the marginal value of each characteristic.

[2]Trees with no clear faces on the 16-foot grading section, or with 1 or 2 clear faces on the 16-foot grading section with sweep in the lower 12 feet of the grading section of more than 3 inches which equals or exceeds one-fourth of the diameter at breast height.

Oriented Strand Board Timber Markets

Stands with a price function having no premium for larger trees, except for logging costs (Case 1), should be planted at high densities, between 800 and 900 trees per acre, have no thinnings, and a rotation age of around 16 years (fig. 1a). This can be referred to as a fiber production rotation. The expectation of increasing manufacturing costs (Case 4 and 6, caused by increases in wax and resin price) should not cause significant changes in management of fiber production rotations (figs. 1b and 3c). However, the value of these rotations decrease noticeably. The value of a fiber production rotation is more sensitive to rotation age then to planting density. Figure 2 presents simulated results from four different planting densities on the total net undiscounted harvest value and volume per cubic foot by diameter class. Since the OSB price function does not place a premium on larger size trees, the optimal regime is to produce more volume in less time. Tree size has only a minor effect related to harvesting costs.

High Speed Sawmill Timber Markets

Three variations in the price function are considered here. The first, an over simplified case but one which is commonly used in optimal stand management studies, deals with stands that have an expected price function increasing with tree size only (Case 2). In this, case no loss is incurred due to quality degrade or restrictions of merchandising wood in the live crown. Near optimal management requires low planting densities (100 trees per acre), no thinning or a precommercial thinning at age 10, and final harvest at around 30 years. In this case, tree size is the driving factor.

A slightly more realistic case is for a stand with a price function increasing with size but with merchandising restrictions (figs. 3a and 3b, Case 8). The merchandising restrictions used in Case 8 are that wood in the live crown or wood above an 8-inch top, which ever comes first, can not be used for sawtimber. The crown ratio equations used are summarized in appendix figure B1. This restriction increases planting density in optimal management regimes, over Case 2. In this case, near optimal management would require planting densities around 200 trees per acre, with a precommercial thin, and final harvest around 32 years. In this case, the effect of tree size is mitigated some by the merchandising restrictions. However, tree size is still the driving factor.

The last case for HSS, Case 10, adds a concern regarding loss of wood quality (increased limbiness) as stand density decreases. (See appendix A for quality loss function.) In this case (figs. 5a and 5b, Case 10), optimal planting densities should be around 400 trees per acre, with a precommercial thinning around age 10, and final harvest around age 40. This planting density is probably an artifact of the assumed value loss function. Four hundred trees per acre is as low as the model will go without loss of quality. No investigation was made of the relation between

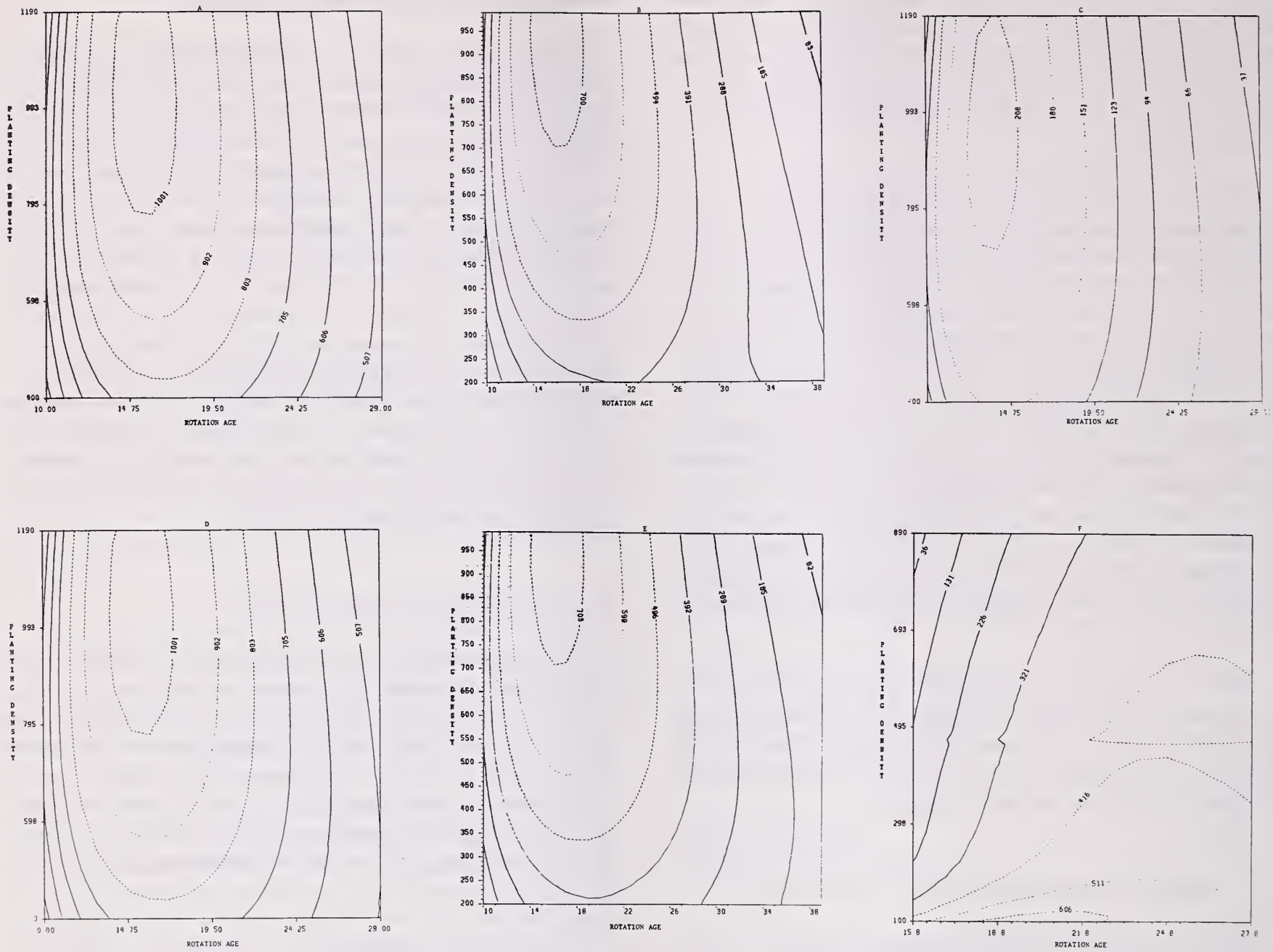


Figure 1.--Soil expectation value as a function of planting density and rotation age for oriented strand board (a, b, c) and mixed market price functions (d, e, f). In figures a and d, the price of wax and resin is at the 1984 market price. The two markets have almost identical results. OSB dominates the HSS price function. In figures b and e, the price of wax and resin is double the 1984 market price. Again, results are almost identical. OSB dominates the HSS price function. In figures c and f, the price of wax and resin is triple the 1984 market price. The differences are obvious. OSB results are the same as in the other cases. OSB is now clearly dominated by the HSS price function.

slope of the value loss function and planting density, or the starting point of the value loss function and planting density. The assumption of value loss is hypothetical and meant merely to illustrate concerns about planting low density. Figure 4 presents the effect of planting density on HSS yield by diameter class. Thinning is precommercial. This type of thin in the optimal solution is at least partially a result of the modeling assumptions. The value loss function is based only on initial planting density not on density after thin. So in order for the model to grow larger trees without value loss, the "best" option is to plant at densities high enough to avoid loss and thin back to lower densities as late as possible but before crowding. The major difference comes at final harvest where lower planting densities result in more larger trees but lower total volume and value. In this case, quality is driving the system as well as tree size and total volume.

A Mixture of OSB and HSS Markets

The final set of cases deal with simple two market combinations. In table 1, five different mixed market cases are listed: 3, 5, 7, 9, and 11. Case 3, figure 1d, has a price function which is a combination of case 1 and 2, OSB at current wax and resin prices, and HSS with price sensitive to diameter alone. This case results in exactly the same optimal regime as OSB alone (Case 1). Thus under these market conditions, a timber grower would

follow a fiber production regime and OSB would have a competitive advantage over saw timber. Case 5, figure 1e, indicates the impact of wax and resin price doubling. The fiber production rotation is still optimal. Note the change in shape of the response surface at lower densities in comparison to figure 1b. This is caused by a sawtimber local minimum, at lower densities and higher rotation age than included on the graph. Case 7, figure 1f, uses the same price function as Case 3, however, with the wax and resin price tripled. The optimum point on this graph is at 100 trees per acre and a rotation of 21 years. When the wax and resin price is tripled, a sawtimber rotation results. The cost of crude oil at the time of this analysis was $18.00 per barrel. If there is a linear relation between oil price and wax and resin price, then oil price can increase up to $36.00 per barrel and OSB regimes would still have a competitive advantage over sawtimber regimes; however, if oil price continues to increase, then somewhere between $36 and $54 per barrel sawtimber would have an advantage over OSB. Effectively, Case 7 has the same optimum as Case 2.

Case 9, figure 3c and 3d, has a price function which is a combination of OSB (Case 4) and HSS (Case 10). Two local optima were found. The largest local optimum has a planting density of 100 trees per acre, precommercial thin at age 10, and final harvest at 22 years. The second optimum has approximately 500 trees per acre, with a commercial thin at age 19 and final harvest at 38 years. Figure 5 presents two planting densities with the price function from Case 9. Note the dark shade is for the OSB market, the light shade is for the timber market. The major difference in the result is that there are more large stems at the lower density.

Case 11 (fig. 5c) has the most realistic price function. It is a combination of OSB (Case 4) and HSS (Case 10). Wood is allocated between OSB and HSS markets depending on where it is more highly valued, or if in the live crown or above an 8-inch top it is allocated to the OSB market. Wood allocated to the HSS market loses value when planting density is less than 400 trees per acre. Only a single optimal point was located. The difference between Case 9 (fig. 3c) and Case 11 (fig. 5c) is the

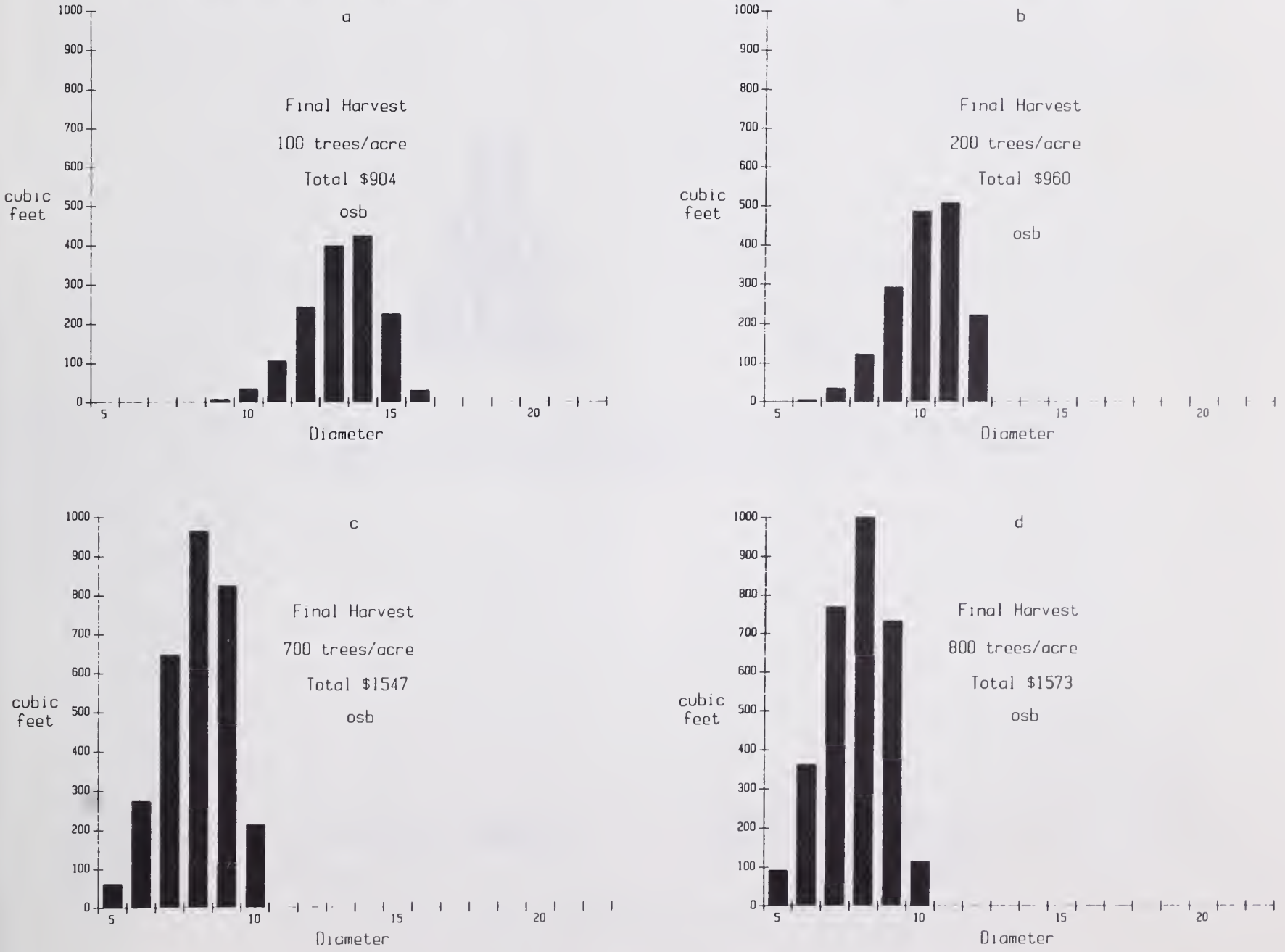


Figure 2.--Final harvest diameter distribution for four different initial planting densities. As planting density increases, average diameter decreases and net harvest value increases. The total net harvest value shown has not been discounted.

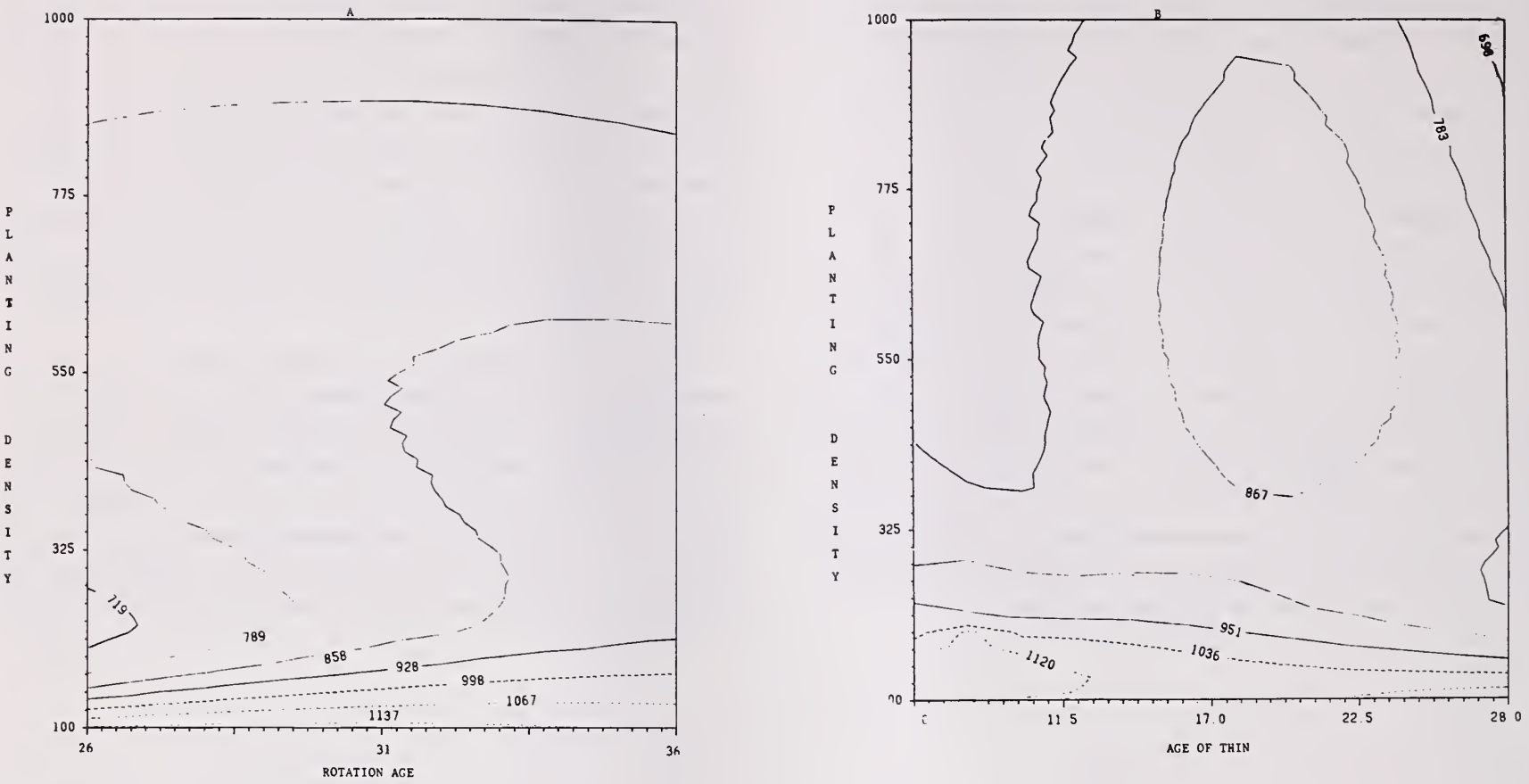


Figure 3.-- Soil expectation value as a function of planting density, rotation age (a and c), and thinning age (b and d) for high speed sawmills (a and b) and mixed markets (c and d).

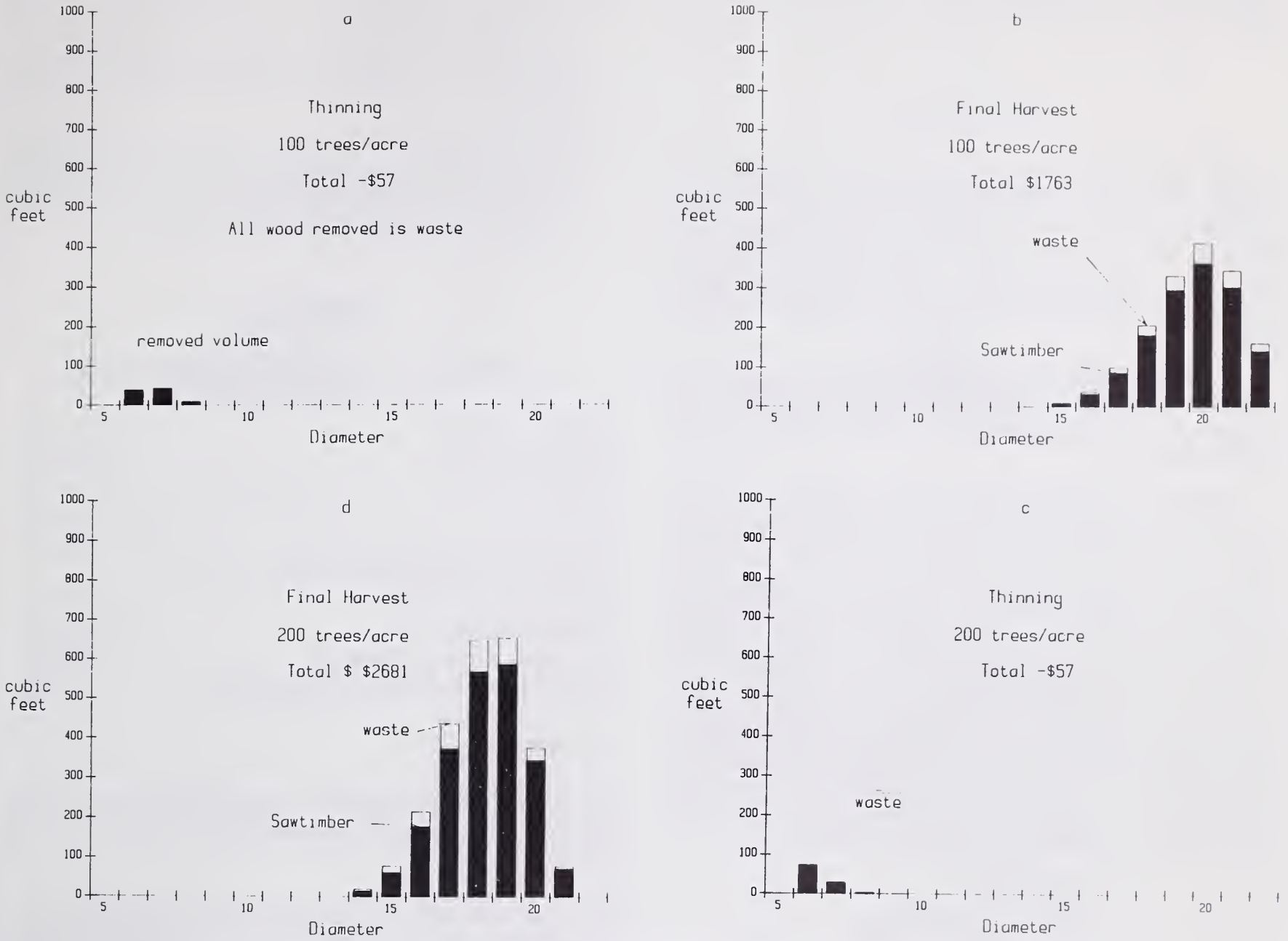


Figure 4.--Diameter distributions of two different planting densities for high speed sawmill markets. The difference between regimes is increased utilization of sawtimber volume because of slightly better tree form at higher density.

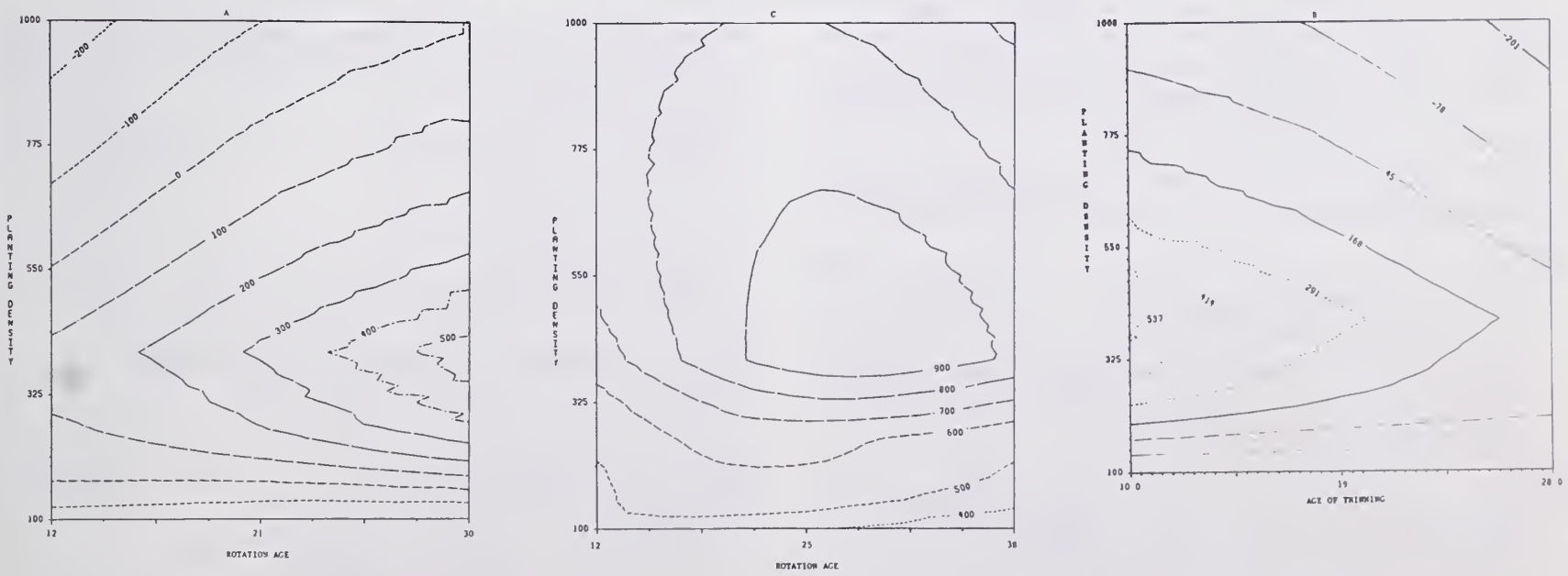


Figure 5.--Soil expectation value as a function of planting density, rotation age, and thinning age for HSS (a and b) and MIX (c) price functions.

value loss at low planting densities. This results in the low density optimum, found in Case 9, being eliminated in Case 11.

CONCLUSION

Each market price function leads to a distinct optimal stand management regime. Constant price functions result in high planting density and short rotations for loblolly pine. Size sensitive price functions result in low planting density and relatively short rotations. Size and quality sensitive price functions result in moderate planting density, a late thin, and late harvest.

The effect of stand density on lumber yield by grade needs further research. The importance of quality on optimal stand management has been demonstrated in this paper, but only for a hypothetical case.

It has been demonstrated here that at current prices of crude oil, OSB has a competitive advantage over solid wood products for a company which produces its own wood. While this could lead to a conclusion that raw wood quality has decreasing significance as a factor in forest management, one must weigh the expectation for future crude oil prices. As a nonrenewable resource, the long term relative price trend can only be up. Leading to an eventuality of OSB losing its competitive advantage over solid wood products. Wood quality may become even more important than it is today. So, given today's markets, management practices should allow for a different market in the future. Obviously, if we knew the future markets for raw wood products, forest management would be far easier.

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APPENDIX A

General Operational and Economic Assumptions

Interest rate (real) 4%
Fixed harvest cost $37.50/acre

Variable logging cost	<7"	8"	10"	12"	14"	16"	18"	20"	25"	30"
$/cubic foot	.34	.27	.23	.20	.18	.17	.16	.15	.14	.14

Transportation cost for 25 miles ..... $0.10/cubic foot
Thinning cost was 53% more than harvest cost
Site preparation cost $78.00/acre
Variable planting cost $0.10/seedling
Sawtimber minimum diameter ..... 8 inches
Oriented stand board minimum diameter ..... none

Site index (base 25) 65

Growth and yield predictions--whole stand diameter/height distribution model for managed loblolly pine--Hafley and Buford (1985).

Row thin every 5th row (remove 20% of basal area) then selection thin remaining stand by removing a variable amount.

Oriented strand board price function (Deal 1986)

1985 cost of resin and wax in output units $27.00/Mft2
1985 cost of resin and wax in input units $0.19/ft3
Wood value at the mill
1985 costs of resin and wax $1.12/ft3
Wood value at the mill
double resin and wax costs $0.93/ft3
Wood value at the mill
triple resin and wax costs $0.74/ft3

High speed sawmill price function (Deal 1986)
(Scraggsaw and headsaw carriage operation)

Variation 1) No adjustments due to density/quality interaction
Value at the mill dbh < 15 inches

value$/ft3 = (-1.97818 + 0.890627 * dbh(1/2)
+ 0.0018964 * height)
dbh ≥ 15 inches
value$/ft3 = (1.36 + 0.0018964 * height)

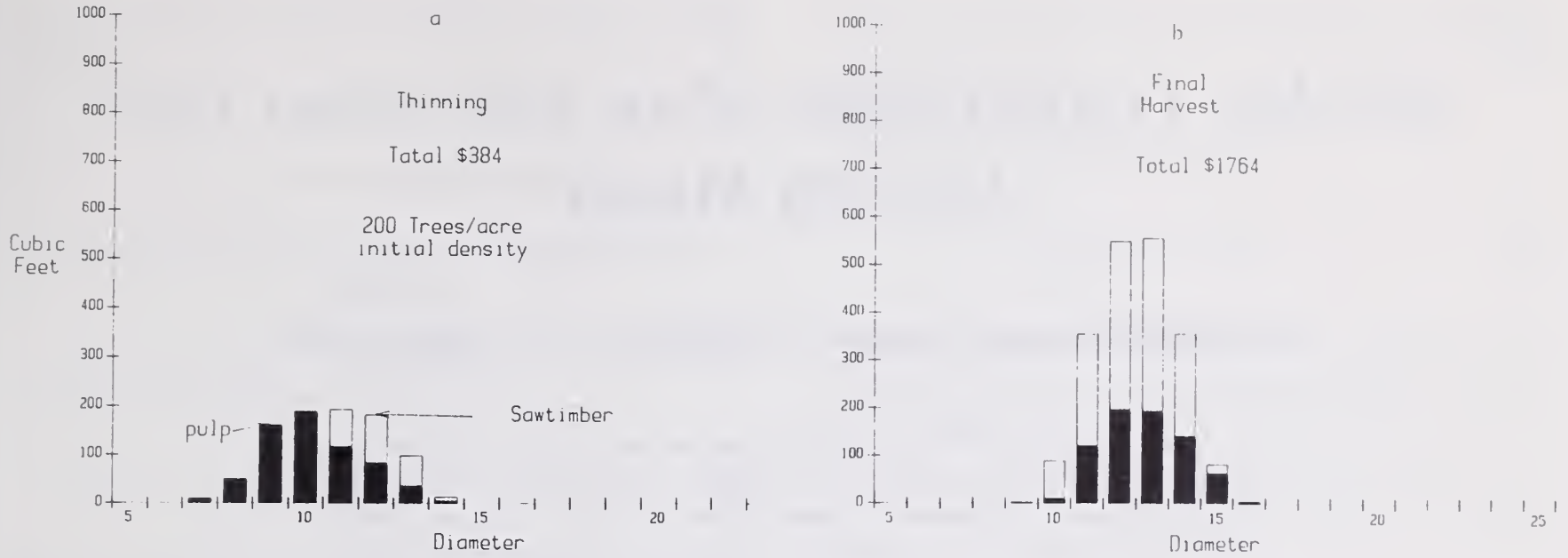


Figure B1.--Diameter distributions at thinning and harvest for two different planting densities and a MIX price function with no price deductions for quality loss.

Variation 2) Only wood below live crown can be used as sawtimber.
Use same function as above for all wood below live crown.
Crown ratio (CR) was calculated as a function of initial spacing (S) and age (A).

$$CR = 2.73986 + 261.398/A + 3.4022 * S - 0.0770436 * A * S$$

At time of thinning CR was calculated using the above equation, at final harvest CR was calculated using either the CR at thinning or the above equation at harvest, which ever estimate for highest crown.
Variation 3) As initial planting density decreases, sawtimber loses quality, therefore value, at a constant rate. Use same functions as above except with the addition of the following value reduction function (R).
if planting density $\geq$ 400 trees/acre then R = 1 (no loss)
if planting density between 100 and 400 trees/acre then

$$R = 0.0033 * (\text{Planting Density}) - 0.33$$

if planting density $\leq$ 100 trees/acre then R = 0 (no value left)
Due to a lack of experimental data this function is hypothetical.
Combination or mixed market price function
This price function assumes that the above two raw wood markets exist equal distances from the stand. The tree is merchandised and allocated to the market of highest value.

APPENDIX B

Crown ratio relation used:

$$CR = 2.73986 + 261.398/AGE + (3.48022 - 0.0770436 * AGE)\ Spacing$$

where CR is the average stand crown ratio
AGE is stand age.
Spacing is the initial tree spacing in feet.
Figure B1 shows the crown ratio relation for five different initial tree spacing.

Efficient Optimization of An Individual Tree Growth Model

Atsushi Yoshimoto, Gonzalo L. Paredes V., J. Douglas Brodie[1]

Abstract.--The PATH algorithm (Paredes and Brodie 1987) is interpreted by means of the calculus of variations. Using the PATH algorithm, a new dynamic programming model called Stand Optimization System (SOS) is developed. The system is incorporated into a growth simulator constructed by Arney (1985). Further limitation of optimality on the PATH algorithm and the relationship between the Lagrange multiplier and the decision variable are discussed.

Determination of the optimal thinning regime and rotation age has been a main problem in even-aged forest stand management. The widespread application of operations research techniques has been contributing to solving the stand level optimization problem. The dynamic programming approach has been developed and extensively applied in recent years.

The dynamic programming approach was applied to the forestry field by Amidon and Akin (1968), Arimizu (1959), and Schreuder (1969). Early scientists used a two-descriptor, i.e., volume and age, dynamic programming model in order to cluster each state (Brodie et al. 1978, Chen et al. 1980, Kilkki and Vaisanen 1970). Brodie and Kao (1979) proposed a three-descriptor dynamic programming model (number of trees, basal area, and age), using an existing stand growth simulator for Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) called DFIT.

This three-descriptor dynamic programming model with forward recursive approach has been extended and adapted for other decision variables and species. Riitters et al. (1982) presented a dynamic programming model with timber production and grazing control joint optimization using a ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) growth model called PPINE. Haight et al. (1985) proposed a dynamic programming model with thinning and rotation age optimization using lodgepole pine (*Pinus contorta* Doug. ex Loud.). A hardwood release and thinning optimization dynamic programming model was constructed for loblolly pine (*Pinus taeda* L.) by Valsta and Brodie (1985). Torres (1987) proposed a thinning optimization dynamic programming model for a *Pinus hartwegii* growth model. In comparison with the above three or more descriptor models, a dynamic programming model optimizing both thinning and rotation age for an individual-tree red pine model (*Pinus resinosa* Ait.) was completed by Martin and Ek (1981) with two descriptors.

Although some of the above models reduced calculation effort to select the optimal activity by using the "neighborhood storage location" technique (Brodie and Kao 1979), dynamic programming still has computational limitations. The more complicated the growth simulator, the more memory and calculations are required (Hann and Brodie 1980).

Paredes and Brodie (1987) resolved the memory and calculation problem by utilizing both network theory and the theory of the Lagrange multipliers. Their efficient way of selecting the optimal path reduced the number of calculations and associated computer storage in comparison with the traditional dynamic programming approach. Since the number of elementary calculations in traditional dynamic programming increases exponentially with problem size, the efficiency is greater with larger problems. However, searching for the optimal value of the Lagrange multiplier remains incomplete. Two other problems called trade-off problems were not dealt with by Paredes and Brodie (1987), one of which deals with situations where no thinning is applied at a certain stage, and the other of which deals with problems associated with insufficient look-ahead period when intensive thinning is applied.

This paper describes and interprets their algorithm (called the PATH algorithm) from a different point of view, in which the technique does not use the Lagrange multiplier. Then a new dynamic programming model is proposed by using the PATH algorithm and a growth simulator called Stand Projection

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System (SPS) (Arney 1985). The trade-off problems are also solved by a new algorithm called Multi-Stage PATH (MSPATH).

OPTIMIZING FORMULATION

The PATH Algorithm by the Lagrange Multiplier Approach

Paredes and Brodie (1987) proposed the optimization problem with the Lagrange multiplier as follows:

$$\max f_N(Y_N) = \sum_{n=1}^{N} A_n(T_n) + \sum_{n=1}^{N} \mu_n[X_n - T_n + G_{n+1}(Y_n)] \qquad [1]$$

where A_n is the return from thinning, Y_n is the stand volume after thinning, X_n is the stand volume before thinning at stage n, G_{n+1} is growth from stage n to stage n+1 based on Y_n, and μ_n is the Lagrange multiplier at stage n. They modified the formulation in the dynamic programming problem as:

$$f_n(Y_n) = \max_{[T_n]}[A_n(T_n) + \mu_n[X_n - T_n + G_{n+1}(Y_n)]] + f_{n-1}(Y_{n-1}) \qquad [2]$$

The PATH algorithm does not utilize the state variables of the growth model for storing the optimal residual stand at each state with a fixed Lagrange multiplier, so that computational task was vastly diminished.

Searching for the optimal level of $[T_n,\mu_n]$, this objective function can be optimized. If the dimensions of both the first term and the second term on the right-hand side of equation [2] are monetary units, the Lagrange multiplier, μ, can be interpreted as the price per unit of resource including its growth potential. In physical objective examples, the Lagrange multiplier can be estimated as simply 1. The control decision concerns both the direct return from the thinning and the return from the future stand. Although it is possible to guess the Lagrange multiplier, it is not always guaranteed that such a value is optimal. Then it is necessary to search for the optimal Lagrange multiplier. The difficulty of searching for the optimal Lagrange multiplier μ_n, can be eliminated by the following procedure.

The PATH Algorithm by the Calculus of Variations

The total return $V(t_n)$ at stage n (time t_n) is the summation of marginal return over time:

$$V(t_n) = \int_{t_0}^{t_n} M(t)\ dt \quad \text{in the continuous case,}$$

$$= \sum_{i=0}^{n} M(t_i) \quad \text{in the discrete case.} \qquad [3]$$

where M(t) is the marginal return at time t. Once thinning, T, is implemented at stage 1 (time t_1), the objective function, $V(t_n)$ is divided into two parts as:

$$V(t_n,T) = \int_{t_0}^{t_1} M(t,T)\ dt + \int_{t_0}^{t_n} M(t,T)\ dt \qquad [4]$$

The first integrand on the right-hand side is equal to the sum of thinning and residual stand after thinning at stage 1. The second integrand represents the sum of growth after thinning from stage 1 to stage n (time t_n). Therefore, $V(t_n,T)$ represents the sum of returns from both thinning at stage 1 and the future stand at stage n. If the optimal thinning regime is required, the objective function becomes:

$$V^*(t_n,T) = \underset{0<[T]\le V(t_1)}{\text{maximize}}\ V(t_n,T)$$

$$= \max\left\{\int_{t_0}^{t_1} M(t,T)\ dt + \int_{t_0}^{t_n} M(t,T)\ dt\right\} \qquad [5]$$

It is obvious that the first integrand on the right hand side is constant because the current thinning cannot affect the previous stand. Then equation [5] becomes:

$$V^*(t_n,T) = \underset{[T]}{\text{maximize}}\ V(t_n,T)$$

$$= V(t_1) + \max_{[T]} \int_{t_0}^{t_n} M(t,T)\ dt \qquad [6]$$

This approach to interpretation of the PATH algorithm is one of the classical calculus of variations problems (Intrilligator 1971). The classical calculus of variations problem is to find the arc lying in a given plane and connecting two specified points in the plane by an arc of shortest length (Dreyfus 1965). Thus, in this context, the classical calculus of variations problem can be interpreted as that of choosing the optimal thinning strategy, which satisfies the boundary condition and maximizes the integral or summation objective functional, V(·).

Schreuder (1971) specified a problem of the optimal strategy for an even-aged forest in the calculus of variations. Although specifying a continuous problem, Schreuder (1971) turned the calculus of variations problem into a dynamic programming problem because when the necessary conditions for an optimum (Dreyfus 1965) were obtained for the general expression, a higher than first-order nonlinear differential equation, such as the Euler equation, resulted. Moreover, even if it could be solved, it would be necessary to investigate numerically all the roots to locate the global maximum because the conditions are only necessary and not sufficient. Then it was impossible for Schreuder (1971) to obtain a closed-form expression.

However, if we know exactly what the objective function looks like, then it is not necessary to solve the Euler equation to obtain a general solution. Furthermore, necessary conditions function as useful tests, which can eliminate candidate solutions, even if they are not sufficient to prove global optimality. After satisfying necessary conditions, it becomes obvious that there is an optimal trajectory. If we have such a trajectory that satisfies a given problem, that trajectory could be optimal.

Let the objective be the maximization of total volume, J, i.e.,

$$\max_{[X]} J = \sum_{n=0}^{N} \int_{t_n}^{t_{n+1}} X'_n \, dt \qquad [7]$$

$$X = (X_0, X_1, X_2, \ldots, X_N) \; X_{N+1}(t_{N+1}) = 0, \; X_0(t_0) = 0$$

where X is a vector describing a thinning regime.

As mentioned by Everett (1963), if the value of X_i is decided independently in each cell, the sum is obviously maximized by simply maximizing the following objective function with respect to X_n, so that we solve recursively:

$$\max_{[X]} J_n = \max_{[X]} \int_{t_n}^{t_{n+1}} X'_n \, dt \qquad [8]$$

In the PATH algorithm, it is assumed that the choice of X_i does not affect the optimal path after the next stage, which is equivalent to the above assumption. The reason is that the stand, which provides the maximum sum of marginal return, or growth during the previous period, seems most likely to create the optimal stand at the next stage. However, there is a case where this assumption does not hold. Such a case is discussed later.

In a given problem, for any $X_n(t)$ satisfying boundary conditions, all necessary conditions provided by Dreyfus (1965) hold. Thus what should be done next is to search for the optimal trajectory among admissible ones. Let's define notation as follows:

Y_n = vector describing the stand at stage n before a decision T_n,

X_n = vector describing the stand at stage n after a decision T_n,

T_n = vector describing the decision variable (thinning) at stage n, transferring the stand X_n into Y_n,

X'_n = stand growth at range (t_n, t_{n+1}).

Therefore, among these variables, some relationships are formulated:

$$X_n + T_n = Y_n \qquad [9]$$

$$X_n + \int_{t_n}^{t_{n+1}} X'_n \, dt = Y_{n+1} \qquad [10]$$

From these equations, the objective function [8] can be converted into the following function:

$$\max_{[X_n]} J_n = \max_{[X_n]} \int_{t_n}^{t_{n+1}} X'_n \, dt$$

$$= \max_{[X_n]} \{ Y_{n+1} - X_n \} \qquad [11]$$

$$= \max_{[T_n]} \{ Y_{n+1} - X_n + T_n \}$$

Since Y_n is constant for all admissible trajectories [the principle of optimality, Dreyfus (1965)], Y_n can be eliminated from the objective function, resulting in the new objective function:

$$\text{maximize } J_n = Y_{n+1} + T_n \qquad [12]$$
$$0 < T_n < Y_n$$

As a result, a sequence of T^*_i which optimizes the objective function [12] in each cell, can constitute the optimal thinning regime maximizing the original objective function [7]. It is also possible to determine the optimal rotation age in terms of maximizing mean annual increment of J with respect to t_{n+1}. In other words, setting up the maximax problem as:

$$\max_{[N]} \max_{[T]} \frac{1}{t_{N+1}} \sum_{n=0}^{N} \int_{t_n}^{t_{n+1}} J(X_n, X'_n, t) \, dt \qquad [13]$$

the optimal rotation age can be obtained at the same time. If the optimal stand at each stage is obtained, equation [13] becomes:

$$\max_{[N]} \max_{[T]} \frac{1}{t_{N+1}} \sum_{n=0}^{N} (Y^*_{n+1} + T^*_n - Y^*_n)$$

$$= \max_{[N]} \frac{1}{t_{N+1}} (T^*_1 + T^*_2 + \cdots + T^*_N + Y^*_{N+1}) \qquad [14]$$

where Y^*_{N+1} and T^*_n (n=1,2,,,N) are the optimal stand volume at age t_{N+1} and optimal thinning level at age t_n, respectively.

Given prices of inputs, outputs, and an appropriate discount rate, the production function can be converted into a net revenue equation where revenues and costs occurring at different points in time are properly discounted. Maximizing this expression yields the optimum patterns of inputs and outputs through time.

Limitation of the Optimality

In the PATH algorithm, it has been assumed that the optimal path at every stage is determined based on evaluations of the stand's reaction at the next stage. In other words, the return from

the future stand is estimated on the basis of the next stage. Then the path provided is optimal as long as it is decided on this criterion, and also if necessary conditions for an optimum, from the calculus of variations problem, hold. However, two interesting situations can develop. The first situation occurs if there is no thinning at the next stage. The second situation occurs in conjunction with intensive thinning, when the look-ahead period is insufficient to evaluate impacts on the future stand. These situations are discussed below.

The Impact on Optimality With no Thinning at the Next Stage and Intensive Thinning at the Current Stage

Let's consider the first situation, at which it is assumed that T_1 at stage 1 is the optimal thinning level on the basis of stage 2, and that there is no thinning at stage 2 based on stage 3. Thus, if sufficient evaluation of the future stand based on stage 3 is done at stage 1, there can be another optimal thinning level, T'1. If T'1 produces more objective value than the path provided by the PATH algorithm, the trade-off has to be evaluated at stage 3.

As for the second situation, it is possible for a stand with few trees to create a great potential growth over the long-term in a complicated stand growth simulator. This discrepancy also violates the assumption of the PATH algorithm that one-stage look-ahead period is sufficient to evaluate impact of the future stand. Then sufficient evaluation of the future stand should be implemented especially for a complicated growth simulator. These two situations suggested the following new PATH algorithm called Multi-Stage PATH (MSPATH) algorithm.

Multi-Stage PATH (MSPATH) Algorithm

The above two situations occur when the look-ahead period is insufficient to evaluate impact on the future stand. The MSPATH algorithm uses each possible look-ahead period at each stage in order to search for the optimal objective value at each future stage based on the different combinations of look-ahead period. In other words, the MSPATH algorithm searches for the optimal combination of look-ahead period from the initial stage to the final stage at the same time when the optimal thinning level is decided. Then MSPATH can decide where one-stage look-ahead is used, two-stage look-ahead is used and so on, and how much the optimal thinning level is for the optimal combination of look-ahead period. Then the optimal thinning regime at each stage can be obtained based on multi-stage look-ahead period. Figure 1 shows the possible combinations of look-ahead period by the MSPATH algorithm.

From the viewpoint of computational burden, MSPATH creates more computation than PATH. However, if the traditional dynamic programming algorithm is used in order to solve the same optimization problem as MSPATH by using SPS, the problem of insufficient look-ahead period also appears. That is,

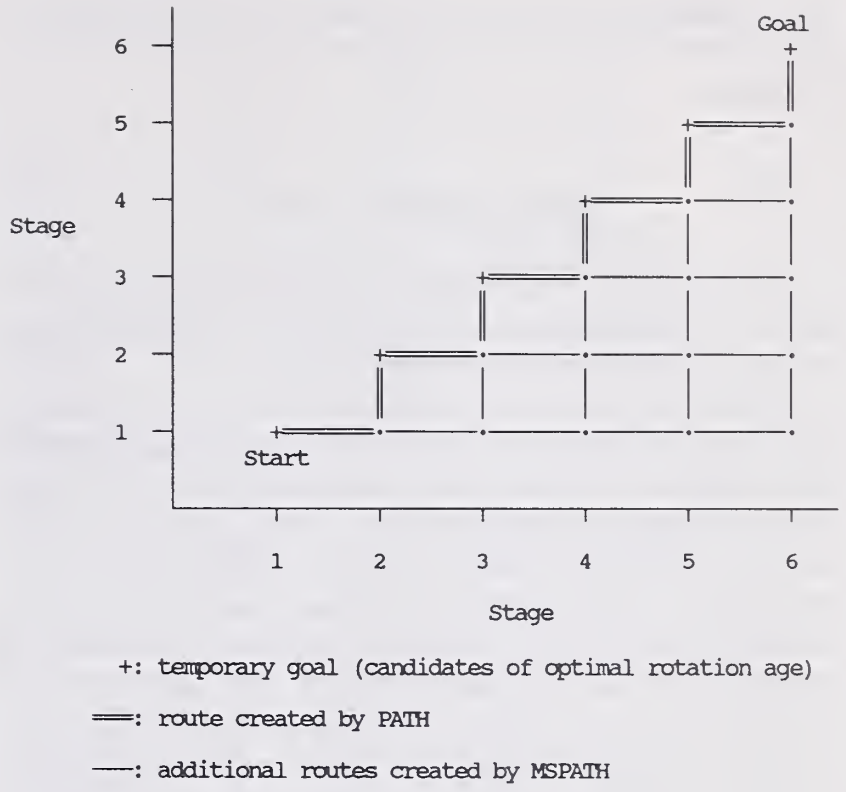


Figure 1.--Possible routes by MSPATH.

with the traditional dynamic programming algorithm, a one-stage look-ahead period, is utilized. Therefore, if a more accurate solution is needed for the traditional dynamic programming algorithm, the same technique as MSPATH utilizes to extend look-ahead period should be implemented. As a result, even if MSPATH creates more computational burden than PATH, it is still efficient in comparison with the traditional dynamic programming algorithm, and provides the optimal solution so long as necessary conditions for a calculus of variations problem hold.

STAND OPTIMIZATION SYSTEM (SOS)

By using the SPS growth simulator (Arney 1985), the Stand Optimization System models (SOS) are proposed with either the PATH algorithm or the MSPATH algorithm. The acronym SOS is used to distinguish the proposed optimization framework from the SPS simulation framework.

The SOS system developed here is classified as a deterministic, single descriptor, discrete-state, discrete-stage dynamic programming model. The problem solved utilizes a forward recursion. While searching for the optimal thinning level at each stage, it is possible for the user to use one of two different criteria in order to select the optimal thinning level.

One of them is such that once the objective value declines, the previous thinning level is labelled optimal. The other is such that after calculating all admissible solutions, the optimal thinning is selected among them. The following procedure is imbedded into the SOS model with the PATH algorithm. Since the basic procedure for the SOS model with the MSPATH

algorithm is the same as the SOS model with PATH, optimization procedure discussion is excluded for the MSPATH algorithm here.

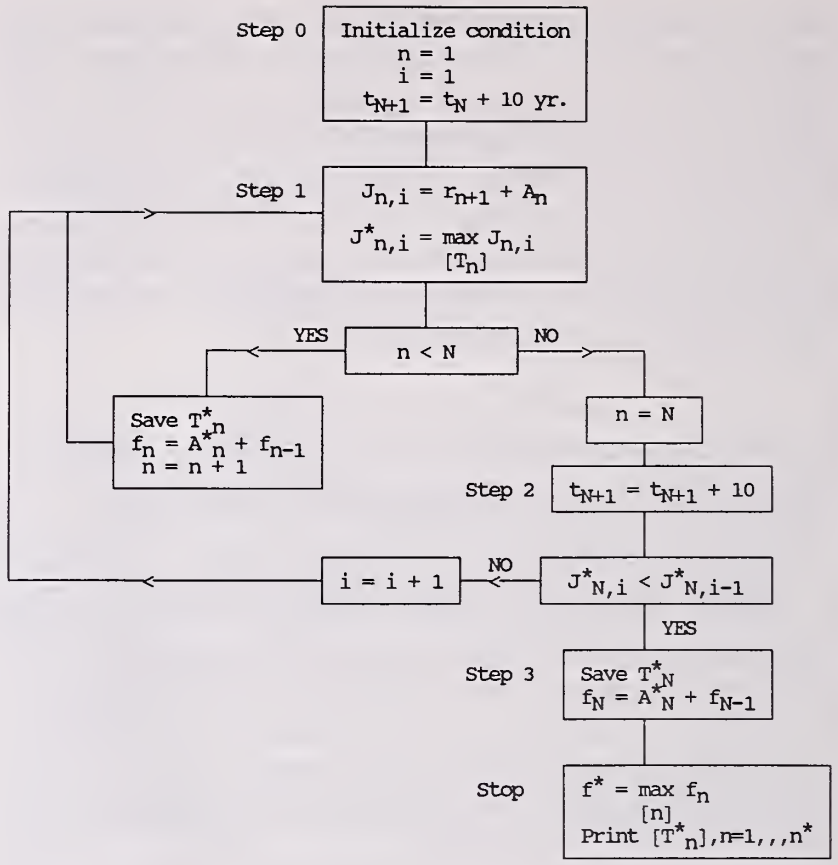
Optimization Procedure

Employing a forward recursion to find the optimal thinning regime and rotation age, SOS searches for the optimal thinning regime at each stage in the following way:

First SOS creates the initial forest stand structure having diameter distribution with individual tree height data and crown ratio data, which result from a yield table given by the user. After thinning an amount of trees, which is decided by the number of iterations calculated, and the interval of node given by the user, i.e., N x Interval, a residual stand grows until the next stage. At this stage, the sum of returns from both thinning and the future stand is compared with the previous one to store the best thinning level so far. If the user selects the first option, i.e., the unimodality assumption, once the objective function declines, SOS quits the iteration at this stage, and decides the previous thinning level is optimal. Otherwise, the iteration is continued until the number of the residual trees is less than the interval of thinning, then the best thinning level among admissible strategies is selected. SOS can also select the optimal thinning method at each stage among thinning from below, thinning from above, and thinning to a cut/residual ratio fixed as 1.

If the thinning method "joint optimization" is selected by the user, after storing the best thinning level for one method at each stage, SOS does the same operation for two other methods so as to search for the best thinning level with each method at each stage. Comparing these three best objective values at each stage provides the optimal thinning method and level at each stage.

After determining the optimal trajectory at this stage, SOS sets up the initial forest structure at the next stage. Iterations continue over state and over stage until the last activity completes searching for the optimal trajectory from the initial stage to last stage. At the last activity, SOS searches for the optimal thinning level and rotation age at the same time by means of increasing rotation age by a 10-year step. In other words, first set rotation age 10 years after last activity, store the best objective value and thinning level. Then add 10 years to the previous rotation age, search for the optimal objective value, then compare the present best value to the previous one. If the previous one is greater than the present one, the previous age is regarded as the optimal rotation age after all activities. However, it is possible for the early stage to have more objective value than the rotation age selected by the above procedure. That is, the above procedure provides the optimal rotation age if the optimal rotation age is later than the last thinning time given by the user. Then SOS searches for the new optimal rotation age again from the initial stage to the rotation age calculated by the above procedure. As a result, optimization of both thinning regime and rotation age is completed. This procedure is summarized in figure 2.



r_n : return generated by residual stand at stage n before a decision

R_n : return generated by residual stand at stage n after a decision

R'_n : sum of marginal return generated by residual stand from stage n to stage n+1 after a decision T_n

A_n : return generated by a decision at stage n

f_n : total return at stage n

N : last stage

Figure 2.--Flowchart of the PATH algorithm.

Features of the SOS Model

The objective function of SOS can be based on mean annual increment of basal area, total cubic feet, merchantable cubic feet or board feet as well as present net worth (PNW), and soil expectation value (SEV).

Combining thinning basis, such as trees per acre (TPA) or crown competition factor (CCF), and thinning method, such as thinning from below, thinning from above, or thinning to a c/r ratio of 1, can provide 2 x 3 = 6 possible thinning regimes. If thinning method joint optimization is selected, SOS indicates not only the optimal thinning level but also the optimal thinning method at each stage on either TPA or CCF basis.

For the sake of making the model simple, cost and revenue from thinning and final harvest are based on entry cost, stumpage price premiums, and other constant silvicultural costs. Entry cost is fixed over time for thinning and final harvest. Price

equation per cubic foot is expressed as a function of DBH, which can be created by using either one linear equation or an equation with several continuous linear segments. It is also possible to utilize a different price equation for different species. These financial data, with interest rate, are utilized for economic optimization and in the financial reports of physical optimization. Although it is possible to use more complicated economic data, such as logging cost identical for each thinning level, cost is limited as above.

Since a price equation transforms a searching surface which is directly derived from physical data into a new surface which has economic information, it is necessary to take into account what kind of price equation can be used. In other words, even if the searching surface obtained from direct physical data is nicely concave, it is possible for it to become an irregular surface when the price equation is included. In such a case, one of the necessary conditions, the Weierstrass condition, which shows the condition for concavity over the control variable (thinning level), would be violated, as well as the Weierstrass-Erdman corner condition. For example, if a step-wise price equation is used, these conditions are not satisfied. This violation is shown by the relationship between the objective function and the decision variable, which would not be concave. Once these conditions are violated, the solution provided by SOS becomes the better solution, and not the best one.

ANALYSIS WITH THE SOS MODEL

Illustrative Example

To demonstrate SOS with both the PATH and MSPATH algorithms, an input file and financial data are required. Characteristics of the data are:

species: Douglas-fir and western hemlock,

site index: 82 of Douglas-fir at 50-year breast-height-age basis,

region: Pacific Northwest Region.

Thinning is implemented at age 20, 30, and 40 years. The basis of thinning is number of trees per acre, and the type of thinning is thinning from below with maximum DBH limit 100 inches (this value should be large so that thinning from below can be implemented at every diameter class).

In addition to this data, tree height, number of trees per acre, breast height age, and percent of crown ratio at each DBH class as well are given in table 1. Also optimization basis, interval of node, and financial data are provided as follows:

optimization basis: soil expectation value(SEV),

interval of node: 20 trees per acre,

interest rate: 4%,

entry cost: $50.00,

Table 1.--An illustrative example (Arney 1985).

	sp	st-id	age	region
Stand	DF	82	10	PNW
Merch	1.0	16.4	5.0	9.0
Name		An illustrative example		

		age basis		method		
Thinning	1	20	1	0	1	100
Thinning	1	30	1	0	1	100
Thinning	1	40	1	0	1	100

Table	SP	DBH	HT	TPA	BT-AGE	CR
1	WH	2	18	15	19	80
2	WH	3	27	92	19	80
3	WH	4	32	227	19	80
4	WH	5	35	121	19	80
5	WH	6	36	41	19	80
6	DF	3	30	32	18	80
7	DF	4	34	57	18	80
8	DF	5	38	138	18	80
9	DF	6	38	72	18	80

Clump	0.85						
Reports	10	20	30	40	50	60	70

coefficient for reducing
thinning value: 0.80,

regeneration cost: $200./acre at age 0,

price/1,000 ft^3: 200xDBH + 80,

As shown in table 2, if all activities are required, the optimal thinning regime and rotation age from the PATH algorithm are:

thinning 180 trees per acre at age 20,

thinning 160 trees per acre at age 30,

thinning 60 trees per acre at age 40,

clearcut at age 50.

However, the results from the MSPATH have different thinning levels at each stage depending upon the temporal rotation age, which is characterized by MSPATH. Figure 3 shows the optimal path from the PATH algorithm in terms of stand volume and figure 4 shows the path from the MSPATH algorithm. Figure 5 shows the searching surfaces over time, which can reveal the actual optimal rotation age. According to figure 5, 30 years is the optimal rotation age for both models, which can differ depending on the economic data.

As expected, however, the difference of the objective value between the PATH algorithm and the MSPATH algorithm is less than 2%, so if the user does not care about this small difference, the PATH algorithm can be recommended to save computational time.

Table 2.--Optimal thinning regime.

	Temporary rotation age									
	20 years		30 years		40 years		50 years		60 years	
AGE	PATH	MSPATH	PATH	MSPATH	PATH	MSPATH	PATH	MSPATH	PATH	MSPATH
20*	702**	702	180	180	180	280	180	360	180	280
30			522	522	160	--	160	--	160	--
40					362	422	60	--	200	340
50							302	342	--	--
60								162	79	
SEV	3268	3268	3644	3644	3457	3555	3108	3179	2762	2799

**Thinning age.*

***Trees per acre.*

-- = no thinning.

SEV = $ per acre.

Relationship Between the Lagrange Multiplier and Optimal Thinning Regime

As mentioned before, the PATH algorithm can be expressed in terms of the Lagrange multiplier as:

$$f_n(Y_n) = \max_{[T_n]}[A_n(T_n) + \mu_n[X_n - T_n + G_{n+1}(Y_n)]] + f_{n-1}(Y_{n-1}) \quad [2]$$

at the n-th stage. The PATH algorithm is also interpreted from a different point of view as:

$$J_n = \max_{[T_n]} [A_n(T_n) + r_{n+1}(Y_{n+1})] \quad [15]$$

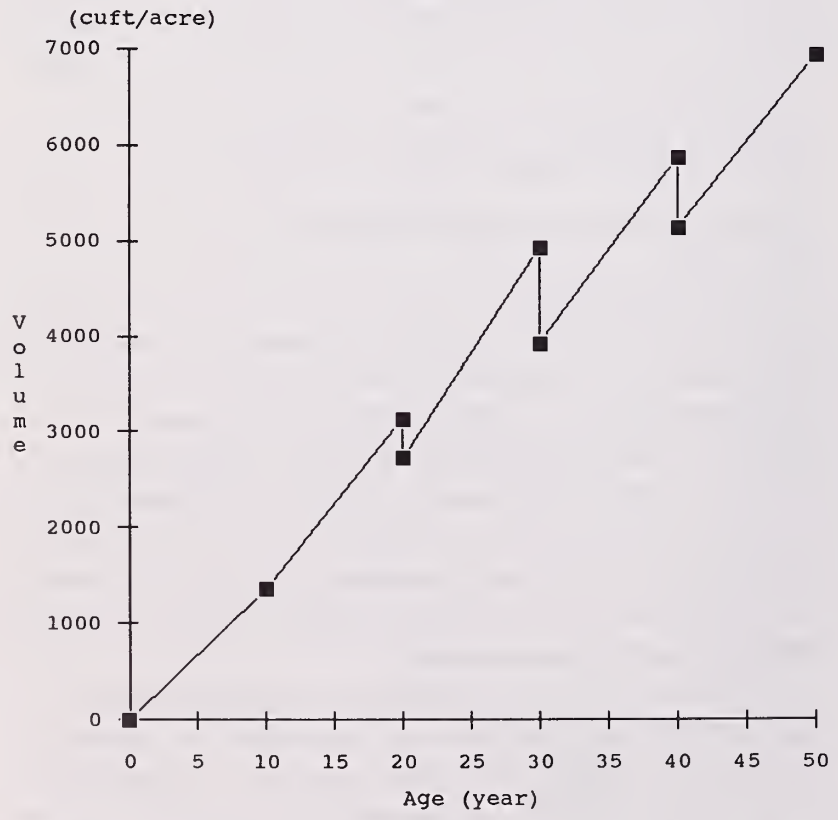


Figure 3.--Optimal thinning regime by the PATH algorithm.

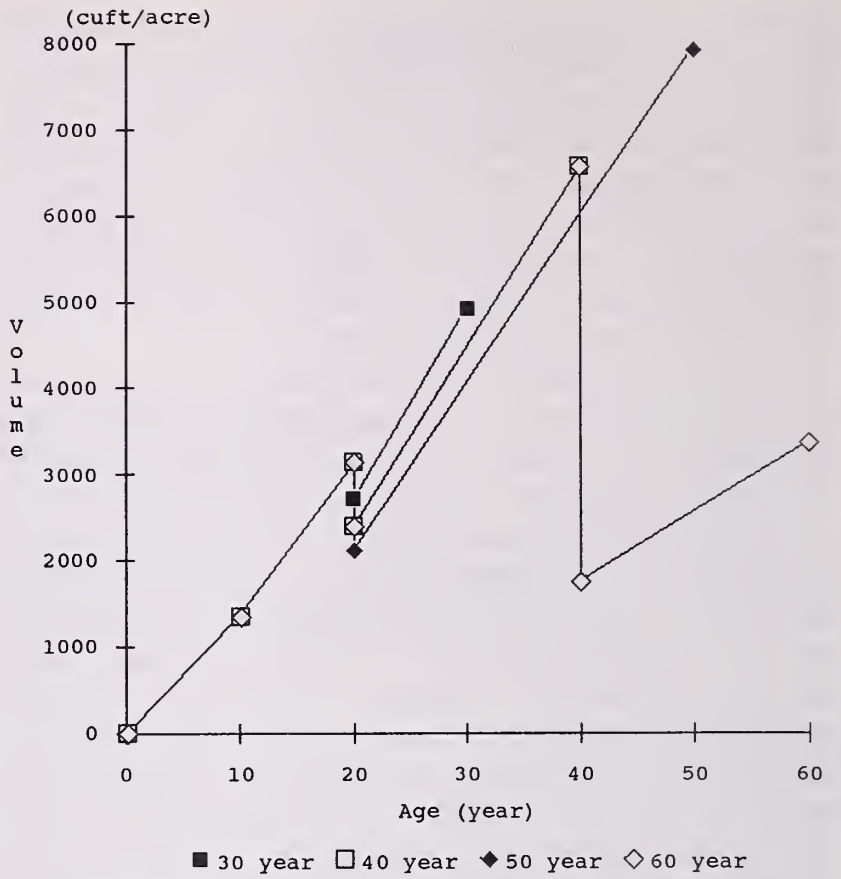


Figure 4.--Optimal thinning regime by the MSPATH algorithm.

Since this objective function does not have the Lagrange multiplier, it is possible to estimate the Lagrange multiplier. Suppose that necessary conditions for a calculus of variations problem hold and sufficient look-ahead period is used. Then if the optimal solution is obtained by the above two functions respectively, the optimal thinning levels obtained by these two methods should coincide as long as the same interval of node is used. Then at the optimal point the following equation is satisfied:

$$A^*_n(T_n) + \mu^*_n[X_n - T_n + G_{n+1}(Y_n)] = A^*_n(T_n) + r^*_{n+1}(Y_{n+1}) \quad [16]$$

Solving for the Lagrange multiplier μ^*_n, we can obtain:

$$\mu^*_n = \frac{r^*_{n+1}(Y_{n+1})}{X_n - T_n + G_{n+1}(Y_n)} \quad \frac{r^*_{n+1}(Y_{n+1})}{Y_{n+1}} \quad [17]$$

Therefore at the optimal point of the n-th stage, the Lagrange multiplier can be interpreted as the average return per unit volume at the (n+1)-th stage. If the basis of optimization is cubic-foot volume, the Lagrange multiplier becomes equal to 1 as was expected by Paredes and Brodie (1987).

Economically speaking, both the Lagrange multiplier and the decision variable correspond with each other. In other words, if the Lagrange multiplier is given, then the decision variable is determined at the optimal point. Then searching for the optimal allocation is limited to the range at which this relationship holds.

Figure 6 shows the relationship between the Lagrange multiplier derived from equation [17] and the decision variable,

thinning level. The higher thinning level, the larger the Lagrange multiplier. Also the greater the stage, the less the Lagrange multiplier.

The Lagrange multiplier derived is interpreted economically not only as the shadow price or the opportunity cost but also as the marginal value per unit volume of resource at each stage by which the maximum attainable value of resource could be increased if an additional unit of resource were to become available (Dorfman 1961, Paredes and Brodie 1987). According to equation [17], the Lagrange multiplier having the above interpretation at each stage should be estimated based on the future stand, not the current.

CONCLUSIONS

The objective of this paper was to develop a new dynamic programming model using the SPS growth simulator (Arney 1985), employing the PATH algorithm (Paredes and Brodie 1987). This model called SOS can optimize both thinning regime and rotation age based on either mean annual increment of the given physical basis, present net worth, or soil expectation value, as long as necessary conditions for a calculus of variations problem hold and one-stage look-ahead period is sufficient to evaluate the future stand. Once either one of these conditions is violated, or one-stage look-ahead period is insufficient, the solution obtained by PATH becomes the better solution, and not the best solution. Then SOS based on the MSPATH algorithm is also proposed in order to solve the optimization problem when one-stage look-ahead period becomes insufficient in evaluating the return from the future stand. However, once a necessary condition is violated, the solution provided by MSPATH becomes better, and not best.

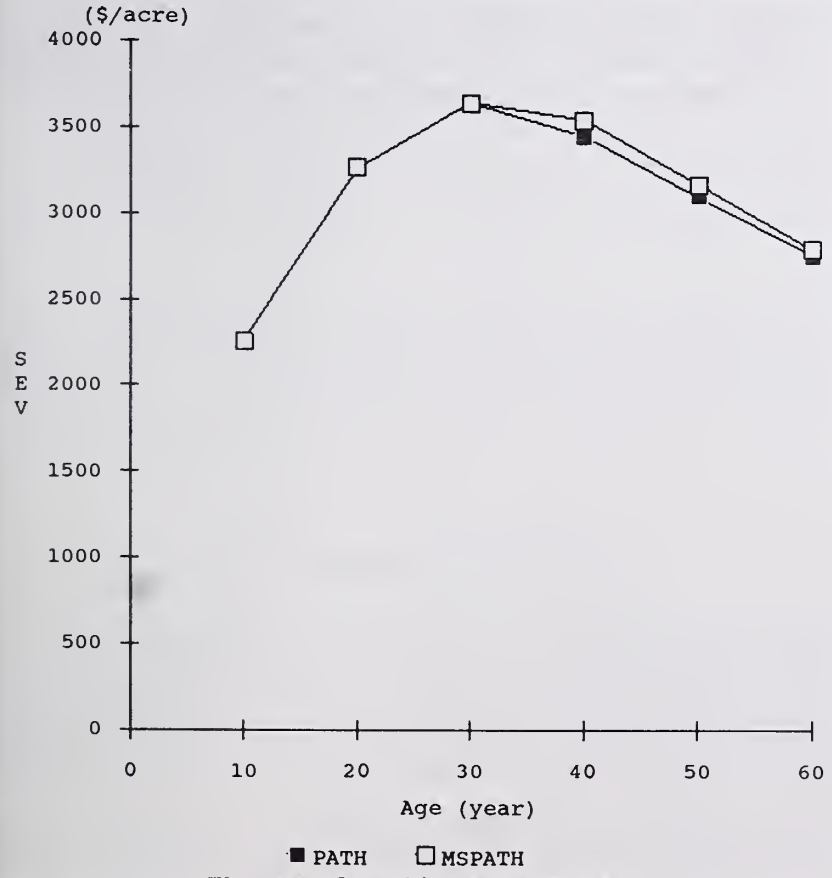


Figure 5.--Searching surface of SEV.

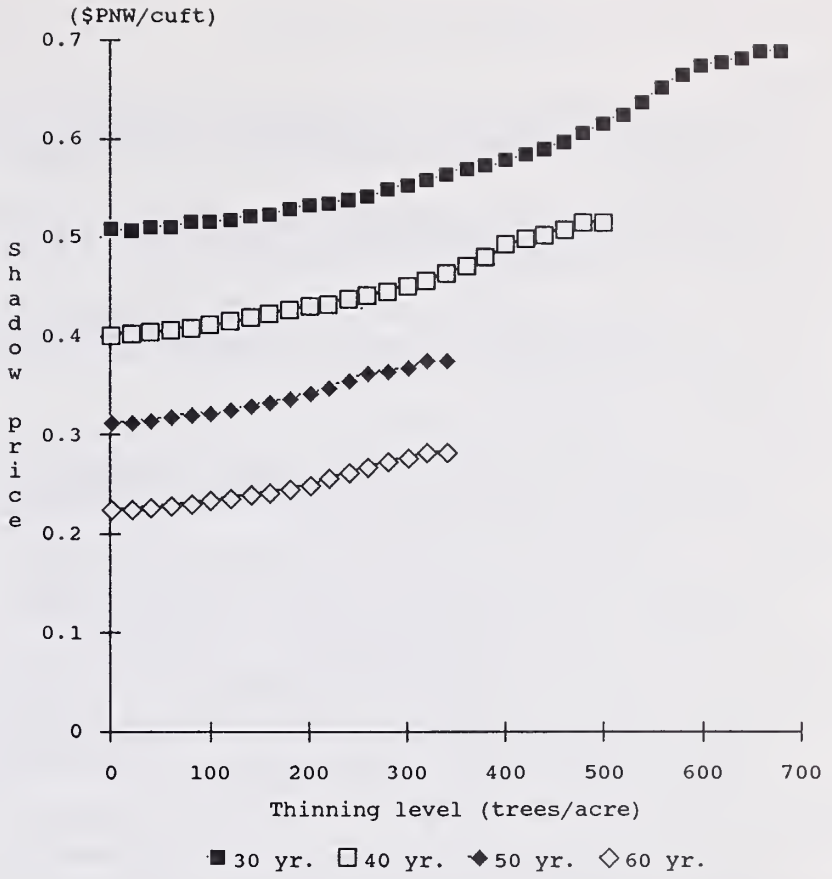


Figure 6.--Relationship between shadow price (Lagrange multiplier) and thinning level.

The modification of the PATH algorithm by the calculus of variations in order not to use the Lagrange multiplier allows one to recognize the efficient PATH algorithm easily. Once the optimal resource allocation is obtained, the optimal value of the Lagrange multiplier can be calculated automatically as well, in terms of the relationship between the objective function with the Lagrange multiplier and without.

Directly treated as a decision variable, the unit thinning level given by the user determines the number of iterations at each stage, or the residual level before thinning divided by the unit thinning level. This technique eliminated so many calculations that the joint optimization of thinning methods and the optimization of rotation age are completed with less computation in one run of SOS than the traditional dynamic programming algorithm. Thus the calculation task and memory required to store optimal stands is vastly diminished to utilize very complex forest stand level production models.

Brodie and Haight (1985) indicate that when thinning from above is incorporated in an optimization model, where growth is driven by top-height a violation of the principle of optimality can occur unless state space is expanded to include top-height. Although SOS growth is driven by top-height, the implied expansion of state space becomes unnecessary through the process of evaluating the future stand (after thinning from above) as part of the objective function. The same problem of suboptimization occurs, however, if the future stand productivity is not projected sufficiently forward. In such case, the MSPATH algorithm can resolve it.

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Concave vs. Convex Singular Path Solutions for Optimal Economic Thinning Schedules in Even-Aged Stands

Matthew T. Turner and David R. Betters[1]

Abstract.--Singular path solutions for economically efficient thinning schedules have been found to have both concave and convex shapes. A concave path indicates the rate of thinning increases with time; a convex path depicts the opposite. The results of this study indicate only convex singular paths should occur for most thinning situations occurring in even-aged stand management.

Optimal economic thinning schedules for even-aged stands have been derived using both dynamic programming and optimal control theory (OCT) techniques. In general, the optimal thinning policy may show the rate of thinning to increase as the stand ages (i.e., concave singular path) or decrease as the stand ages (i.e., convex singular path).

Several recent studies using dynamic programming show the optimal thinning policy to involve a decreasing rate of thinning as time progresses, thus mimicking a convex singular path (Amidon and Akin 1968, Brodie et al. 1978, Brodie and Kao 1979, Chen et al. 1980). Using OCT, Cawrse et al. (1984) and Donnelly (1986) derived convex time paths for thinning. On the other hand, Clark (1976) and Clark and DePree (1979) developed concave paths for the optimal thinning policy (fig. 1).

The purpose of this paper is to explore what factors might lead to convex versus concave singular path solutions for the optimal economic thinning problem. The study concentrates on comparing the OCT work cited above along with empirical analysis of similar formulations.

OCT Singular Path Solutions

In OCT a singular arc occurs when the Hamiltonian is linear in the control variable. The control (e.g., thinning harvest) is determined by the requirement that the coefficient of the linear terms remain zero along the singular arc (Bryson and Ho 1975).

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In the case at hand, the control variable for thinning is linear and the OCT approach does result in a singular path solution. Further, since the control is linear, the Euler-Lagrange condition from classical calculus of variations may be used to determine the singular solution (Pfaffenberger and Walker 1976). Clark (1976), Clark and DePree (1979), and Cawrse et al. (1984) all applied the Euler-Lagrange condition to determine the singular path. The formulations were similar in terms of the objective functional (present net value based on an infinite series) varying only by the state equations used for stand growth. Clark used a Gompertz function while Cawrse used a logistics function. Since this was the only key difference between the studies, our research effort focused on the growth functions influence on the shape of the singular arc.

The growth function, or state growth, for Clark's work was

$$\frac{dv}{dt} = at^{-b}ve^{-cv} - h(t)$$

where

at^{-b} is a monotonically decreasing function of time which tends toward zero as the stand ages. It serves as a check on the growth, which without this function would always depict positive growth after thinning regardless of stand age,

c is a coefficient,

v is stand volume per acre,

h(t) is the thinning harvest volume, and

ve^{-cv} is the standard Gompertz function.

And for Cawrse's work the growth function, or state equation, was

$$\frac{dv}{dt} = at^{-b}rv(1-\frac{v}{k}) - h(t)$$

where

r and k are coefficients,

$rv(1 - \frac{v}{k})$ is the logistics function,

and all other terms are as defined previously.

Since these growth functions monotonically decrease with time, all singular paths must eventually decrease with time. However, the rate of the decrease may increase (concavity) or decrease (convexity) with time.

Application of the Euler-Lagrange condition to the objective functional with these state equations resulted in the singular path for Clark's work as

$$(1 - cv)\, e^{-cv} = \frac{1}{at^{-b}} \left[-\frac{\dot{R}(t)}{R(t)} + \alpha\right]$$

and the singular path for Cawrse's work as

$$V = \frac{k}{2} - \frac{k}{2ar} - \frac{1}{at^{-b}} \left[-\frac{\dot{R}(t)}{R(t)} + \alpha\right]$$

where

R(t) is the net revenue from thinning at time t and R.(t) its rate of change, and

α is the annual discount rate.

Numerical Analysis Solutions

There isn't any straightforward method to analytically determine whether the singular paths are concave or convex. Therefore, the singular path for Clark's work was derived using the Newton-Raphson algorithm (Burden et al. 1981). This algorithm uses the singular path function, its first derivative, and the Taylor expansion series to estimate values for the optimal path. The singular path values for Cawrse's work were developed using a computer spreadsheet program.

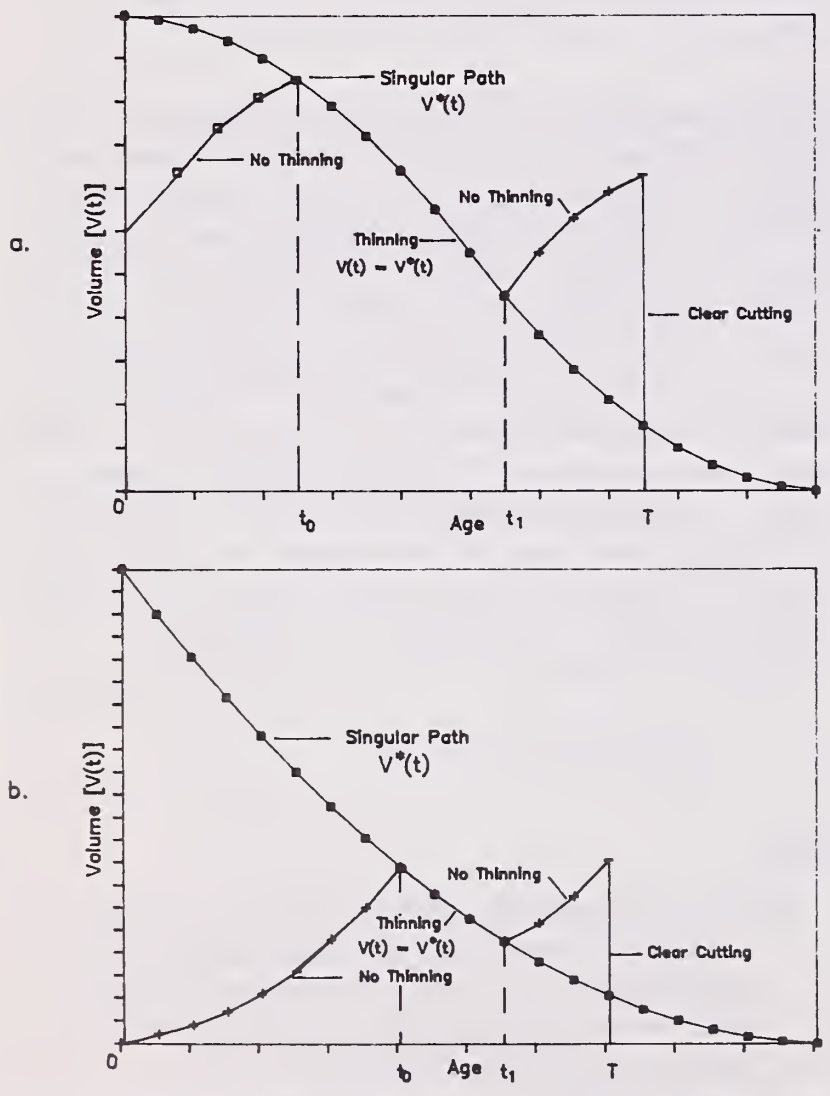


Figure 1.--Concave (Clark 1976) labeled "a," vs. Convex (Cawrse et al. 1984) labeled "b," singular path solutions where v is stand volume and t is time in years. Concavity is defined in relation to the graph origin or mathematically as $f[\theta t_2 + (1-\theta)t_1] \geq \theta f(t_2) + (1 + \theta) f(t_1)$ where f is the singular path, $t_1 < t_2$ are times, and $0 \leq \theta \leq 1$. For a convexity definition, the $\geq$ is changed to a $\leq$.

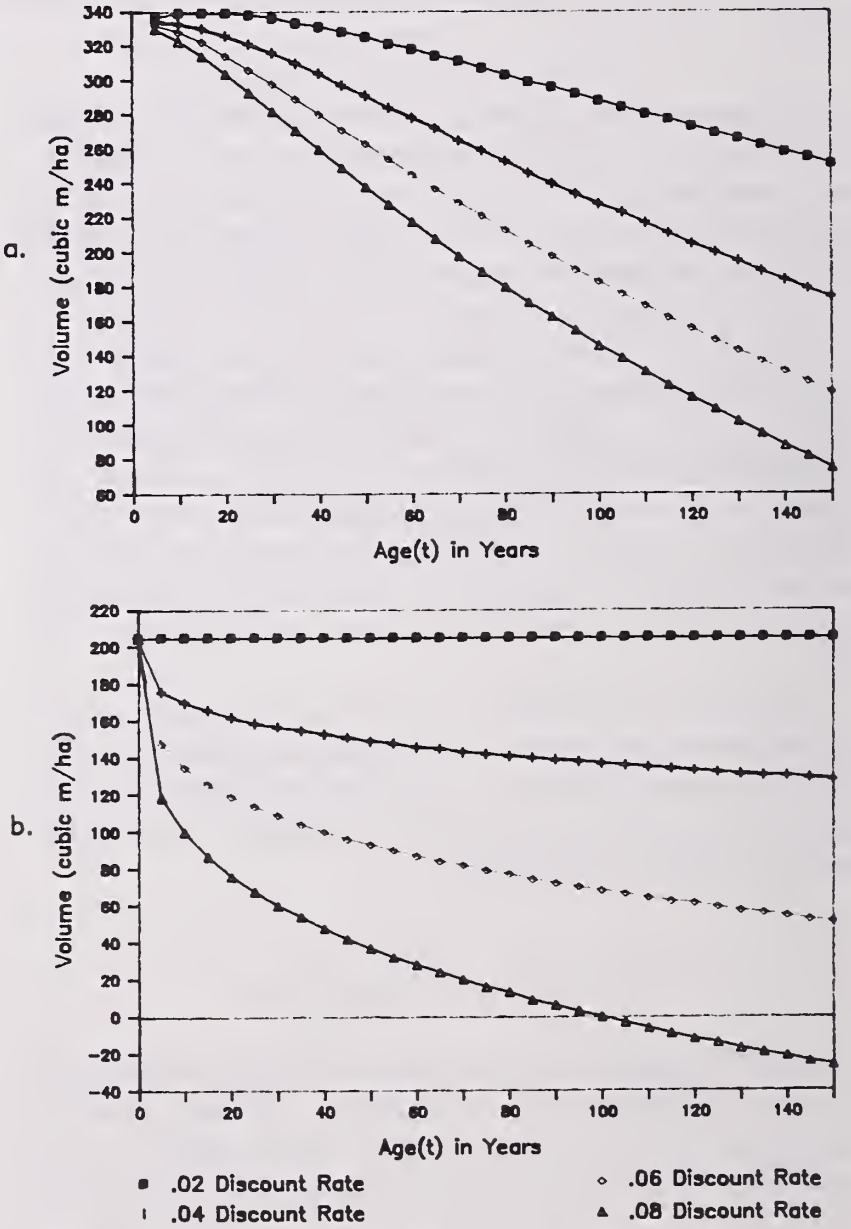


Figure 2.--Convex singular paths for Clark and DePree (1975), labeled "a," and Cawrse et al. (1984), labeled "b," data sets derived through numerical analysis.

In the initial analysis, the same growth and economic parameters used by Clark and Cawrse were applied to attempt to reproduce their results. In Cawrse's case, the paths derived were identical to those shown in that study. On the other hand, we derived convex paths for Clark's singular solutions rather than the concave curves reported in his work (fig. 2). After testing several combinations of growth and economic parameters, the singular solutions remained convex. The singular paths are not concave as Clark's studies suggest.[2] The question then arises whether or not convex paths are the general case for these type problems, or are they only the case for these two studies?

A second numerical analysis was made using a Gompertz equation with economic data from Kilkki and Vaisanen (1969) and using a logistics equation fit to net yield tables for lodgepole pine (Dahms 1964). In both cases, the numerical analysis again resulted in convex singular paths.

Conclusions and Implications

These empirical tests support the conclusion that the OCT singular path solutions to the even-aged thinning problem should generally be convex. This convexity should increase as the discount rate increases. Thus, as a general policy, if thinnings are to be applied in an optimal financial manner, the rate of thinning should decline over time and the growing stock become more stable as the stand ages (that is, until it is completely removed, normally via a clearcut). This policy is largely a consequence of higher thinning costs relative to the volume of growth and the increasing impact of the discounting factor as time passes.[3]

Many renewable resources follow growth patterns similar to that depicted by the growth functions used in this analysis. If the resource is renewed periodically, such as is the case for even-aged stands, and the economic relationships are similar, one might expect that convex singular paths would also describe the optimal economic policy for those cases.

As a practical tool, the family of singular path solutions can be used to help determine thinning rates and stocking levels for any given rate of return or where rates of return may change during the course of a stand's growth. For example, at any stand age, t, the stand stocking and estimate of the thinning rate for various discount rates, can be read directly from the graph of singular paths. As such, the curves do provide management guidelines for general thinning strategies.

Although these empirical results are not all encompassing, for most thinning situations commonplace to forestry, OCT optimal singular path solutions would appear to be convex in nature.

[2]A personal communication with Colin Clark indicated that errors in the application of the analysis package they used resulted in mistakes in numerical estimates of the singular path solutions. He confirmed the fact that their curves should be convex.

[3]The importance of discounting is emphasized by the fact that without discounting (i.e., discount rate of 0) the optimal policy is to not have any thinnings and to clearcut the stand when growth discontinues, i.e., when ddvt = 0.

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Optimal Stocking of Species by Diameter Class for Even-aged Mid-to-Late Rotation Appalachian Hardwoods

Joseph P. Roise, Joosang Chung, and Chris B. LeDoux[1]

Abstract.--Nonlinear programming (NP) is applied to the problem of finding optimal thinning and harvest regimes simultaneously with species mix and diameter class distribution. Optimal results for given cases are reported. Results of the NP optimization are compared with prescriptions developed by Appalachian hardwood silviculturists.

To achieve the desired objective from any thinning, it is necessary to regulate stand density, stand structure, stand quality, and species composition (Marquis et al. 1984). Consideration of all these variables simultaneously can represent a major computational challenge. However, several recent studies using nonlinear programming (NP) techniques appear to have overcome the computational limitations imposed by traditional optimization techniques. New perspectives on formulation and solution techniques have made simultaneous determination of optimal thinning plan, including timing, selection of species by diameter class, and rotation length, a tractable problem. Several recently published papers have explored these new perspectives. Roise (1986c) showed that the class of nonlinear programming algorithms referred to as nonlinear derivative free techniques can be used to optimize a wide variety of simulation problems, including optimal residual diameter class selections. Brooke et al. (1984) has reported significant progress in optimization of high level modeling systems using nonlinear programming. The optimization of simulation models is becoming more accessible.

The purpose of this paper is to present study results from an optimal species by diameter class stocking control problem. The optimal thinning plan and rotation length is solved for an Appalachian mixed hardwood stand using the MANAGE hardwood stand management simulator (LeDoux 1986a) incorporated into the Hook and Jeeves (1962) NP technique.

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The following section briefly reviews the historical background on stand level decision makings. In the subsequent section, the general mathematical formulation for stand level decision makings is stated. Next, the model and the results of its application to a 1-acre Appalachian hardwood stand are described.

Background

As stated by Hann and Brodie (1980), stand level decision making involves such basic problems as finding the optimal species mix, planting density, thinning plan, fertilization plan, and rotation length. The literature indicates that most stand level optimization studies reduced the problem to simultaneously determining the optimal thinning regimes and rotation length. This reduction is probably because of the large number of variables necessary and the resulting computational burden when all variables are included.

Hann and Brodie (1980) further stated that nonlinear programming may have potential. The computational ability of several NP algorithms for even-aged stand management optimization have shown to be flexible optimization tools by Kao and Brodie (1980) and Roise (1984, 1986a). NP techniques have been used earlier to find optimal conversion strategies for uneven-aged stands (Adams and Ek 1974). Uneven-aged stand management has received a great deal of recent advance and clarification using nonlinear methods.

Haight (1987) has used the gradient projection method to solve uneven-aged stand management problems. Haight and Getz (1987) used a penalty function and gradient nonlinear

programming method to compare optimal transition harvest regimes with either fixed end point or equilibrium end point constraints. They solve for the species composition and stand structure which optimize transition regimes and steady state condition. They conclude that solving for an optimal steady state and then solving for the optimal transition to that steady state will in general find suboptimal regimes when compared to solving for a more general equilibrium endpoint and transition regime simultaneously. Bare and Opalach (1987) used a direct search, derivative free, constrained nonlinear programming algorithm to solve for the optimal sustainable equilibrium diameter distribution and species mix in distance independent individual tree growth model.

For even-aged management, NP has not received as much attention. Kao and Brodie (1980) used a "modified flexible polyhedron method" to solve for the optimal thinning plan and rotation length. It is a modification of the simplex method of Nelder and Mead (1964) for constrained nonlinear programming. They also made a comparison between NP and DP by solving the same example problem with both techniques.

Roise (1986a) compared three NP techniques and discrete DP. The three NP techniques were the simplex method of Nelder and Mead, Hook and Jeeves' method, and Powell's method, all of which are derivative free multidimensional optimization techniques for unconstrained problems. He applied three different techniques to an example stocking control problem. He observed that the Hook and Jeeves' method performed better than others with regard to the relative computational efficiency and robustness of convergence for the given example.

Roise (1986b) applied Hook and Jeeves' method to solving for optimal thinning regimes including optimal diameter class distribution. The following section briefly describes his unconstrained objective function derivation procedures. Two advantages of this formulation in increasing the computational efficiency of Hook and Jeeves' method were observed: (1) the separable functional form of the dynamic stocking control was well suited for coordinate optimization and (2) empty diameter classes reduced the number of active variables to be evaluated.

Mathematical Programming Formulation

The mixed species forest stand management problem can be formulated in terms of timing and intensity of thinnings and final harvest.

$$\text{Max } f(t_j, X_{ijn}, t_{T+1}) \qquad [1]$$

subject to

	$i = 1,2,...,N$
$X_{ijn} \in \Omega$	$j = 1,2,...,T$
$H_{ijn} >= X_{ijn}$	$n = 1,2,...,S$
$t_j, X_{ijn}, H_{ijn} \geq 0$	

where N is the number of diameter classes per species; S is the number of species; T is the number of thinnings; f is the objective function; X_{ijn} is the amount of timber to remove from diameter class i and species n at thinning j; H_{ijn} is the amount of species n in diameter class i at thinning j, $H_{ijn} = g[(H_{k(j-p)n} - X_{k(j-p)n}, t_j]$, $p = 1,2,...,j-1$, $k = 1,2,...N$, where g is a growth and yield model with decision variables of size class thinning intensity by species and interval between thinnings; Ω represents the operational constraints of the production system; t_j is the time between thinning j-1 to j; and t_{T+1} is the elapsed time between the last thinning and final harvest.

Assuming that there are no external production constraints, the number of decision variables required is TNS+T+1. The number of decision variables represents the maximum possible problem size. This will be discussed in more detail later when discussing problem reduction.

In order to solve problem [1] using Hook and Jeeves' method, the formulation is transformed into an unconstrained objective functional form as outlined by Roise (1986a). The transformed formulation is

$$\text{MAX } f(t'_j, r'_{ijn}, t'_{T+1}) \qquad [2]$$

where t'_j, r'_{ijn}, and t'_{T+1} are transformed decision variables t_j, X_{ijn}, and t_{T+1}, respectively. This unconstrained function can be solved by any unconstrained optimization technique including Hook and Jeeves' method. Formulation [2] can be interpreted as a barrier function. This formulation enables simultaneous optimization of the time of thinnings, amount of trees to remove for each diameter class by species, and rotation length.

Optimization and Simulation Model Description

All optimization procedures have two parts: the optimization algorithm and the system model. Hook and Jeeves' algorithm and the MANAGE stand management simulator are the two parts used here. Hook and Jeeves' algorithm controls the iteration processes to reach a local optimum point by adjusting decision variables. It is not within the scope of this article to discuss how to determine the global optimum, which is known as an unsolvable problem using NP when the system model is nonconvex. The system model, MANAGE, evaluates the decision variables passed from the Hook and Jeeves' algorithm and passes back an evaluation of present net worth.

MANAGE is a complete management systems simulator for mixed hardwood stands. It consists of a stand growth and yield simulator, GROW (Brand 1981), a thinning and harvest production estimator, ECOST (LeDoux 1985), a tree conversion model, BUCKING (Ledoux 1986b), and economic analysis model, PNW (LeDoux 1983). It includes a number of options which reflect various management activities in the real world. Only the PNW objective function option is used. The decision variables from the Hook and Jeeves' algorithm, the removal ratio of all species by diameter classes and thinning times, are passed to MANAGE. MANAGE removes the specified number of trees for each class, bucks the stems, and estimates present

net value according to log grade values and net conversion costs. The estimated PNW for each entry is summed and passed to the Hook and Jeeves' algorithm where it is considered an objective function valuation, given decision variables.

The Hook and Jeeves' algorithm is illustrated in figure 1. The algorithm searches for the local optimum with a two step method: exploratory and pattern searches. Exploratory searches are directional steps along all coordinate axes from a fixed point, called the "base point." When exploratory searches are completed for all directions, the function gradient is estimated and the search continues in that direction. This movement along the gradient is called a "Pattern Search." The two step searching method is repeated until all the exploratory searches fail to improve the objective value. After successful searches for time variables or pattern searches, the stand conditions are stored for the next iteration to take advantage of dynamic stand structure. If an exploratory search fails, the step size is reduced by some percent of previous step size. It iterates until the step size decreases below a set tolerance. At this time, the last base point is reported as the local optimal solution.

Application to Example Stand Problem

Data from an example 1-acre stand was provided from the USDA Forest Service (Morgantown, WV). The example stand is 70 years old with site index 70. Average stand d.b.h. is 13.3 inches. The stand has 135 trees composed of multiple species such as basswood, hardmaple, white oak, red oak, beech, yellow-poplar, cucumbertree, and other minor species. Among the species, the first four species are considered economically valuable and others less so. The economically less important species were grouped as "Other Hardwoods" for the analysis. A total of 31 species, including "Other hardwoods," are appeas-

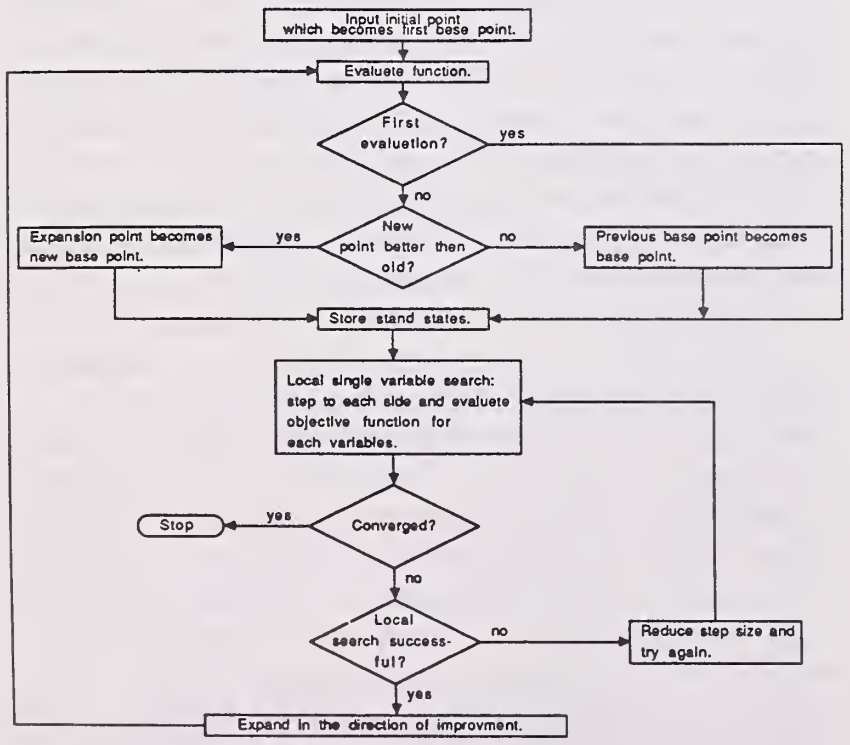


Figure 1.--Flowchart of the Hook and Jeeves' method.

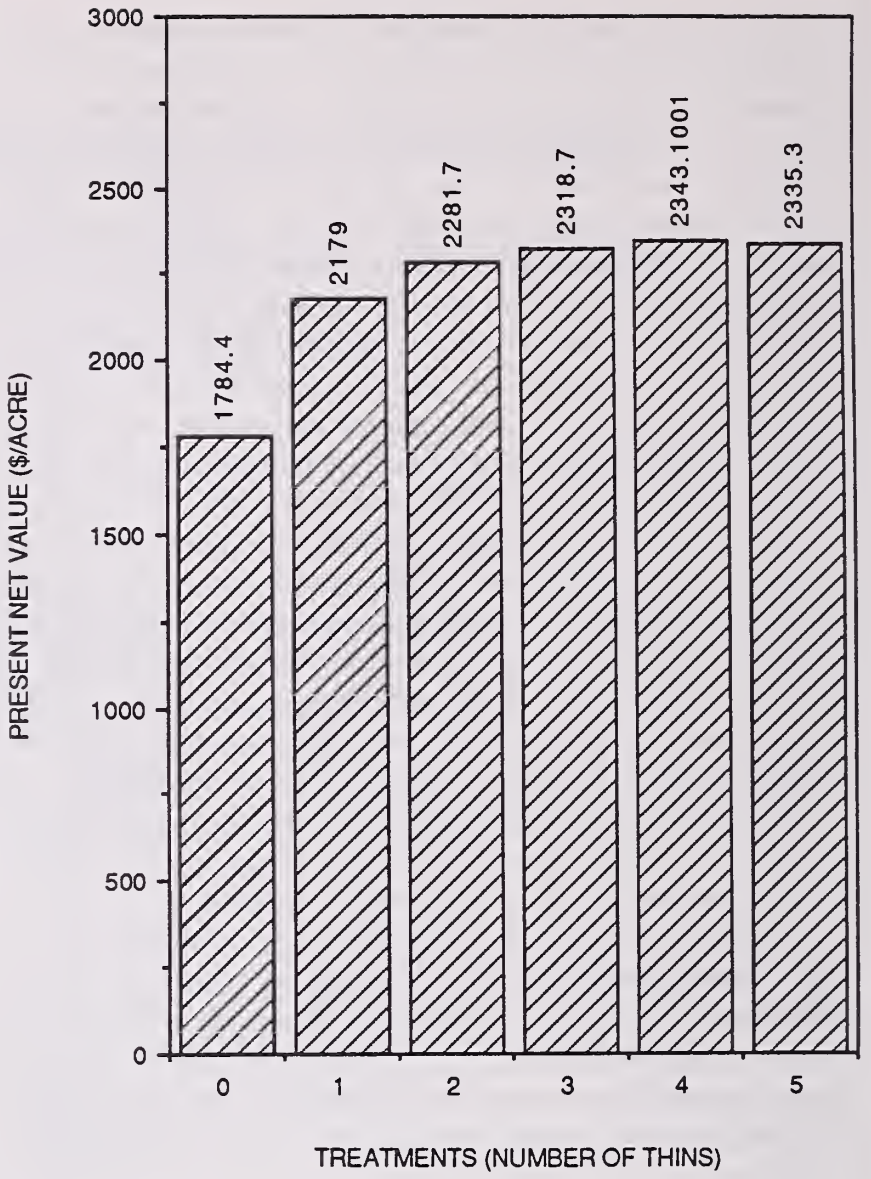


Figure 2.--Comparison of best local optima found with 0 to 5 thinnings.

able. The initial stand structure at age 70 is shown in figure 4 as diameter distributions by species. Real annual interest is assumed to be 4%. The Ecologger I skyline yarding machine is the logging option used.

The objective is to maximize PNW with decision variables of timing and intensity of thinning and final harvest. The number of species, the number of diameter classes, and the number of thinnings determine the total number of decision variables required. In this example, the initial stand has 5 species, including "Other hardwoods." Twenty five 2-inch diameter classes per species are used. This allows for all possible growth projections, as it turns out only 15 diameter classes were needed. At this age, precommercial thinning is not an option. Starting from zero thinning, we increased the number of thinnings by one in each subsequent run until the peak of the local optimal point is recognized (fig. 2). Results are summarized in table 1.

Each number of thinning type was solved three times with different randomly selected initial points (matrix of decision variables). All other non-control parameters remain fixed. When one or more thinnings are involved, the three runs converge on separate local optimum. This is an expected result

Table 1.--Summary of results from three different initial points for six different numbers of thinnings.

No. of thins	Initial point $/ac	PNW $/ha	NFE	Local optimal $/ac	PNW $/ha
0	1780.6	4398.1	6	1784.4	4407.5
0	751.9	1857.2	15	1784.4	4407.5
0	321.9	795.1	18	1784.4	4407.5
1	1092.6	2698.7	821	2179.0	5382.1
1	1004.2	2480.4	1321	2166.9	5352.2
1	1384.7	3420.2	1550	2124.0	5246.3
2	1294.6	3197.7	1035	2281.7	5635.8
2	830.2	2050.6	1347	2234.6	5519.5
2	1448.9	3578.8	1421	2261.8	5586.6
3	1407.9	3477.5	1319	2318.7	5727.2
3	1510.9	3731.9	1584	2318.6	5726.9
3	1543.0	3811.2	1124	2309.5	5704.5
4	1390.4	3434.3	1992	2343.1	5787.5
4	1231.9	3042.8	2598	2315.1	5718.3
4	1081.0	2670.1	2267	2232.0	5513.0
5	1217.9	3008.2	2095	2335.3	5768.2
5	1380.3	3409.3	1517	2307.4	5699.3
5	1047.3	2586.8	2167	2309.8	5705.2

if the objective function is nonconvex (Roise 1986a). Nonconvexity results among other reasons from sigmoidal individual tree growth functions, discrete thinning events, and nonlinear tree value functions (Roise 1986b). NP techniques may or may not provide a global optimum for nonconvex problems. By comparing several runs starting from different points, we may find the best optimal solution. However, the global optimum can never be guaranteed in solving nonconvex problems.

The best optimal solution from zero to five thinnings are compared in figure 2. Objective value reaches a peak at four thinnings and then decreases at five thinnings. When there are five thinnings, one thinning time interval goes to zero in two of the three runs from different initial points. This indicates that for those two, five thinning initial points, the local optima found has only four thinnings.

The number of functional evaluations (NFE) is used as a measure for the computational efficiency. The total NFE required generally increases as the number of active variables increase because more exploratory searches are required. Moreover, different initial matrices of decision variables can results in wide fluctuation of NFE, since some may start much closer to the optimum than others. Figure 3 illustrates the convergence rates of all 15 runs, when the number of thinning is greater than or equal to one. NFE ranges from approximately 800 to 2,598 according to the number of thinnings and the initial matrix of decision variables. In general, 90% of a local optimum PNW is reached within 25% to 30% of total NFE.

The number of decision variables represents the problem size. The problem size was reduced greatly by taking advantage of empty diameter classes as specified by Roise (1986b). The NP algorithm searches only in the vector space of active

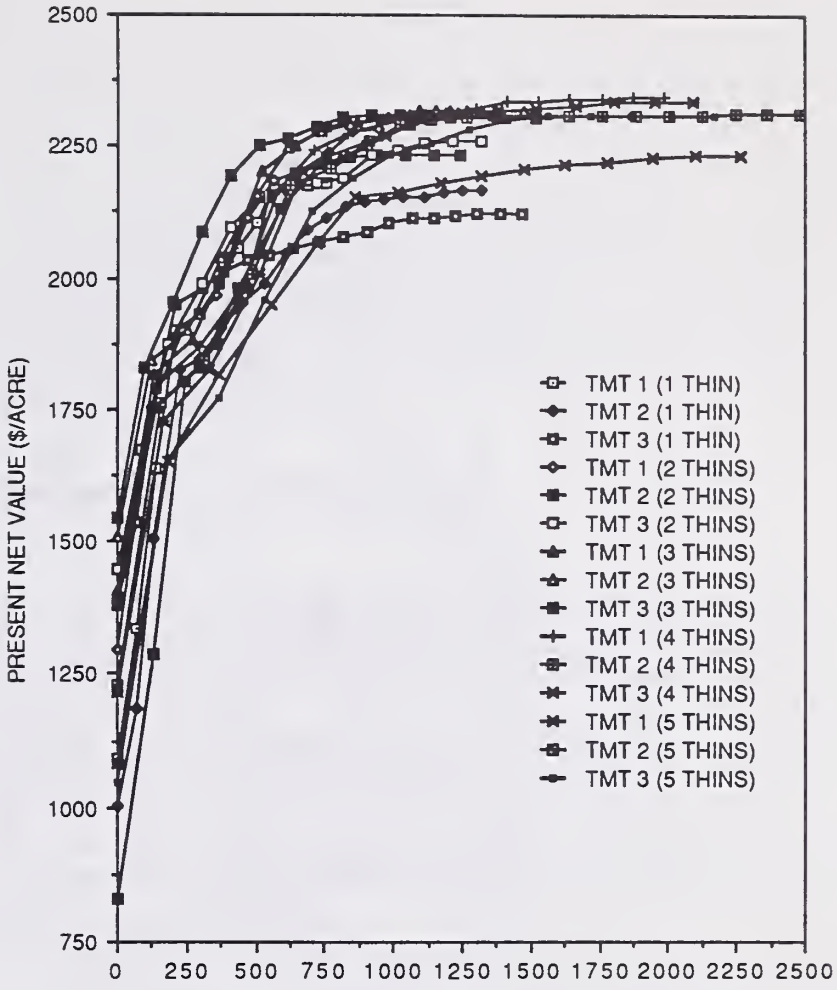


Figure 3.--Convergence rates for treatments from different initial points.

variables. As shown in table 2, the number of active variables was only 18% to 28% of the total variables for treatments with more than two thinnings. This reduction is related to the number of occupied diameter classes in the initial stand structure, the growth rate of species on the stand, and harvesting practices. The ratio of active to total variables for a Douglas-fir stand was observed to be approximately 0.3 by Roise (1986b).

For illustration, the results of the example problem, stand structure by species over time, are shown in figure 4. This was the best optimal solution for all 19 runs. Thinning entries occur at age 70, 90, 120, and 150 and final harvest at age 160. In general, trees are removed from the upper diameter classes. The discrepancy between the number of residual trees of a graph and

Table 2.--Reduction of the number of variables.

No. of thins	Total no. of variables	Aver. no. of active var.	Ratio
0	1	1	1.00
1	77	46	0.60
2	253	70	0.28
3	379	86	0.23
4	505	99	0.20
5	631	109	0.17

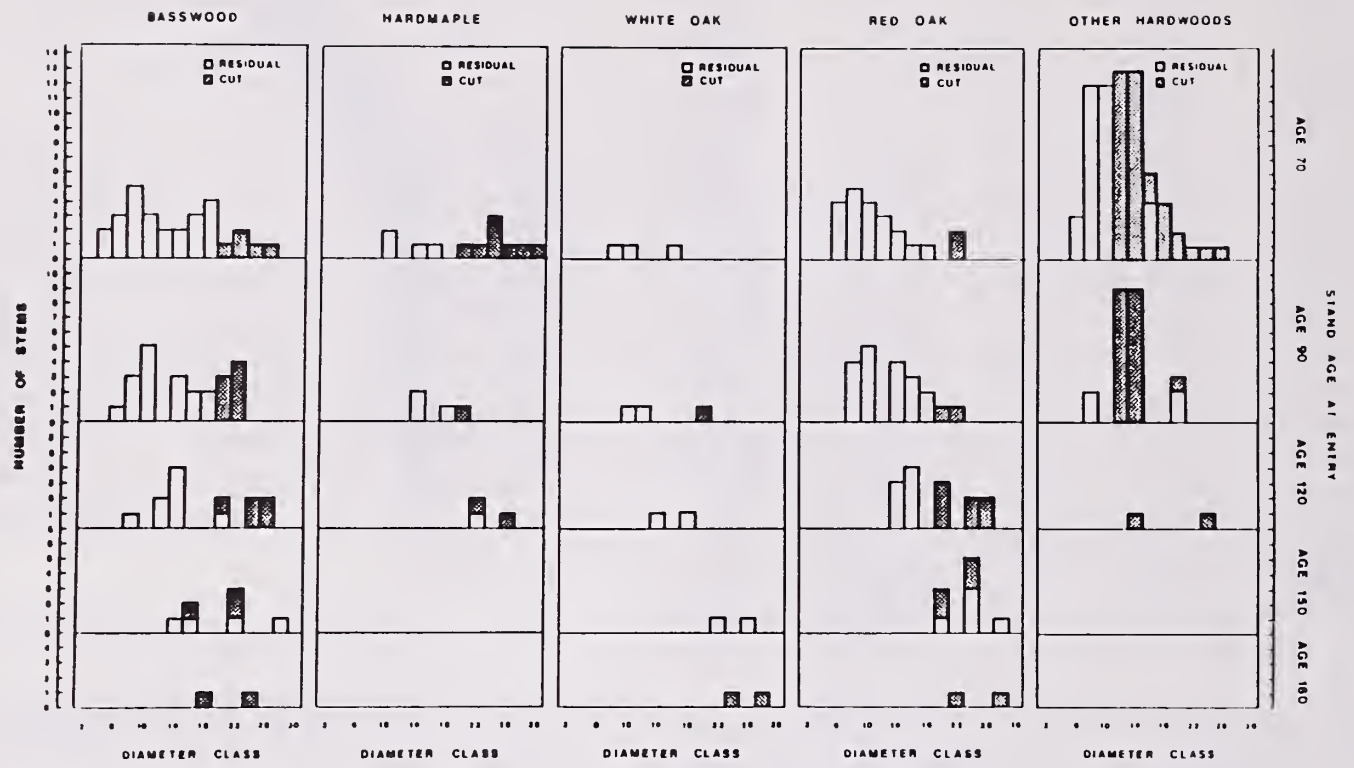


Figure 4.--Diameter class distribution before and after each thinning and final harvest.

the total number of stems in next graph is caused by mortality during that growth period.

How do these results compare to what a silviculturist would prescribe for the stand? To examine this question, we used the method of the prescribing silvicultural treatments in hardwood stands of the Alleghenies which Marquis et al. (1984) developed. Comparison is made on results from their method with results from our method for the first thinning. It should be noted that there is a major difference in objective between the two sets of results. Our objective is to maximize present net value of the stand explicitly considering expensive cable logging technology and detailed stump-to-mill costs. The silvicultural objective is to maximize the net undiscounted value of the stand.

> "Our guidelines on financial maturity are based on studies of individual tree financial maturity in New York, Pennsylvania, and West Virginia (Grisez and Mendel 1972, Mendel et al. 1973), plus unpublished results of computer simulator runs in Allegheny hardwood stands of varying species composition. Financial maturity of the stands in these computer runs was defined as the culmination of mean annual increment in dollar value. No interest rates or present net worth calculations were involved." (Marquis et al. 1984)

The method prescribes the distribution of cuts summarized in table 3 and illustrated in figure 5.

As can be seen, our method cuts trees exclusively from large diameter classes, whereas the silvicultural method prescribes cutting over all diameter classes, except in the sapling classes where both methods prescribe no cutting. In describing a commercial thinning, Marquis et al. (1984) state that trees should be removed primarily from the smallest and largest sizes, retaining those that are inbetween since these are the ones increasing most rapidly in value as they grow into size class they qualify for grade 1 sawtimber or veneer. Our method ignores the smaller sizes and increases cutting in the large to medium sizes. However, it should be noted that our method concentrates the first thinning on removal of low value species from the overstory and only cuts high value species with diameters greater than 20 inches. This is in agreement with the prescription developed using Marquis et al. (1984).

Our method also prescribes a much more intensive thinning than the silviculturists': residual basal area of 53 vs. 92 square feet per acre. There are several reasons for this difference. Our method cuts a much higher amount than what the silvicultural method prescribes because of inventory holding costs and expensive skyline cable stump-to-mill costs that must be offset

Table 3.--Comparison of results between methods of Marquis et al. and Roise et al. (basal area, ft²/acre).

Size class	Original stand	Cut	Residual stand	Cut	Residual stand
		Marquis et al.		*Roise et al.*	
Saplings	0.2	0.0	0.2	0.0	0.2
Poles	21.2	21.2	0.0	0.0	21.2
Small saw	50.1	5.0	45.1	26.9	23.2
Med. saw	40.5	12.2	28.3	31.6	8.8
Large saw	36.0	18.0	18.0	36.0	0.0

at each thinning. However, silviculturists are quick to point out that reducing a hardwood stand to such a low density will lead to problems later: lower tree quality, increased understory of interfering plants, and increased wind damage. Epicormic branching, forking, and other detrimental effects or costs may become serious at relative densities below 60% or 70%.

In general, thinning tends to increase competing understory and may lead to regeneration difficulties later in the rotation.

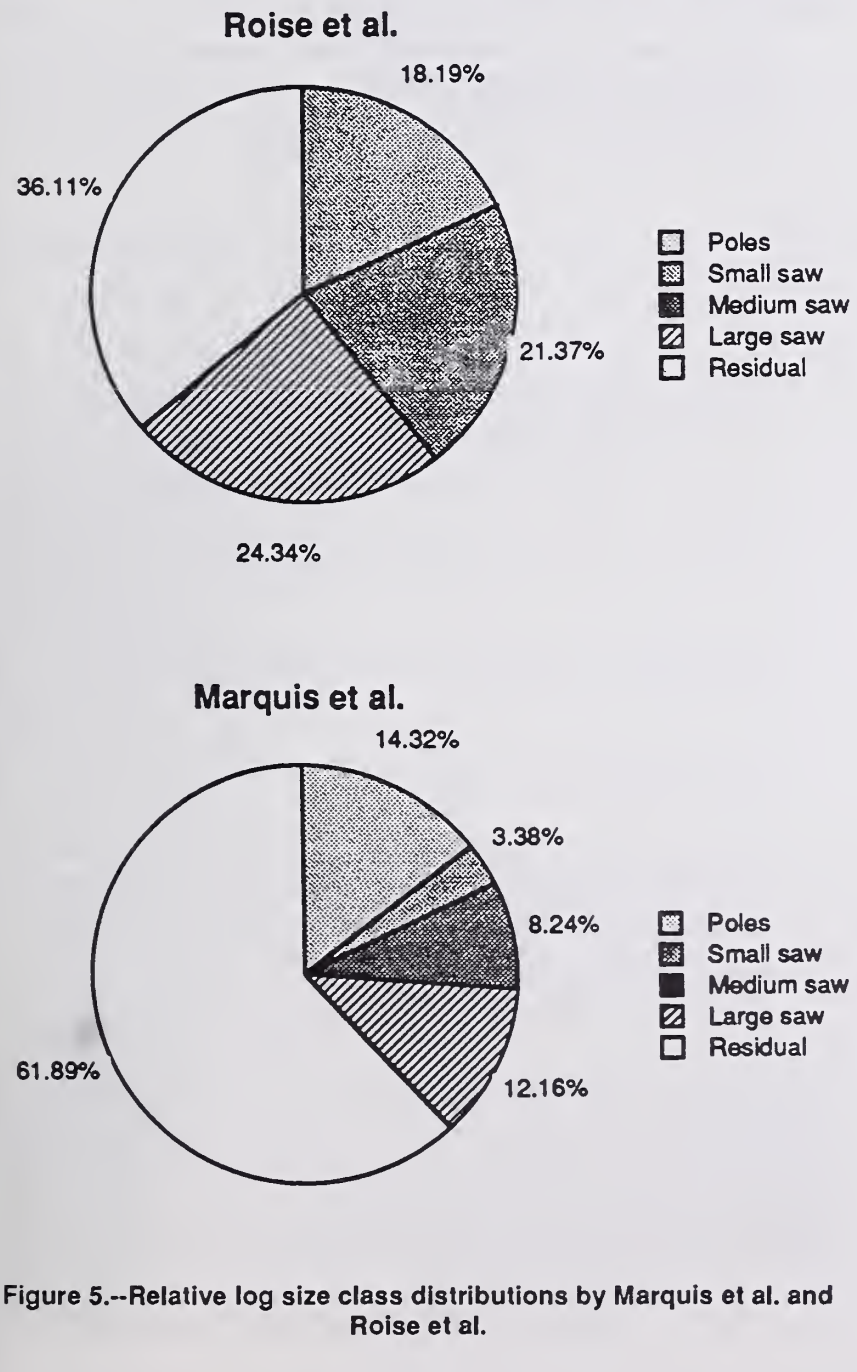


Figure 5.--Relative log size class distributions by Marquis et al. and Roise et al.

Intensive thinning opens a stand up to wind pressures which the root system cannot immediately absorb. This increases risk of windthrow in the stand. In the paper by Roise (1988), found in this same volume, the importance of stand quality is shown. Three stand parameters--volume production, tree size, and quality--are shown to control optimal stand management. All of the above factors are reasons cited by silviculturists not to have low residual densities. The results from the two methods are different because they have different objectives, they use different growth estimation routines and they have different assumptions on logging technology.

Conclusion

The typical Central Appalachian hardwood stand is a complex mixture of species and sizes. The problem of finding the optimal species mix by diameter class over time has a large number of variables. The use of the empty diameter class concept reduces number of variables and enables more efficient solution of the problem. Knowledge of desired species and diameter class structure is indispensable for foresters to make sound stand management decisions. This technique can be used to gain such a knowledge.

In this study, we expand the application of the Hook and Jeeves' method to multiple species problems. The solution to the stand management problem for multiple species stands are obtainable. As the numbers of active variables increase, the NFEs required to converge increase rapidly as well. Use of empty diameter classes and dynamic structures will reduce NFE and computer expense.

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General Analysis and Project Identification in National Forest Planning: A Discussion

Thomas R. Mitchell[1]

Abstract.--Site-specific analysis of Forest Plan direction is often done during implementation through various methods of "area analysis" or "implementation schedules." Such ground truthing of results from general analysis follows a traditional planning pattern. However, Forest Planning is a departure from such traditional planning. Thus rather than a separate, post planning analysis, it may be both appropriate and possible to accomplish more site specific identification of projects during Forest Planning. A discussion of accomplishing this type of analysis while also meeting the more general analysis requirements of Forest Planning is presented.

Context

Forest Planning--

what is it?

what is it suppose to accomplish?

are concepts underlying more traditional analyses such as timber harvest scheduling appropriate?

what level of detail should be included in analyses supporting Forest Plans?

what level of detail should be included in the Plans themselves?

is there a more efficient way to structure a FORPLAN model?

what enhancements in analysis tools appear appropriate?

is Forest Planning so different than anything that we have done in the past that it requires abandonment of procedures and concepts that were used successfully in the past and the development of new procedures and concepts? If so, what are these new concepts and/or analysis procedures?

Each of us comes to this meeting with our own answers to these questions, whether or not we have ever consciously addressed them. As you answer these for yourself, bringing to bear your own unique knowledge, skills, and experiences, each of you will have very different answers than anyone else. If each of us has a different perception of what the "problem" is, how can we discuss or evaluate the effectiveness of basic analysis procedures, and/or enhancements to those procedures to solving the "problem." It would appear that there is a need to discuss what the "problem" is that Forest Planning is attempting to solve as a initial step in discussions of ways to efficiently and effectively perform appropriate analysis.

I believe that such a dialogue was begun by Margo Garcia in her paper at the last Systems Analysis Symposium (Garcia 1985). I would like to use her paper as a basis for this paper. However, rather than dealing with a discussion of general planning theories, I have chosen to explore a definition of the analysis problem posed by Forest Planning in context of timber analyses required as part of Forest Planning.

In this exploration, three interrelated points are discussed. First is that timber analyses necessary to support Forest Planning are more comprehensive than analyses included in conventional timber harvest scheduling. Second, because of this, there is a need to shift from a mixed scanning viewpoint for planning and analysis to a systems approach (Garcia 1985, Mitchell 1975, Mouzelis 1968). And third, even though the same analysis tools can be used, this shift in the frame of reference for analysis requires different modeling/analysis techniques than conventionally applied.

Background

For almost 400 years, timber analysis and implementation of results of analysis appear to have followed a mixed scanning

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approach. That is, a high level decision based on analysis is made regarding the amount of volume or acres to be harvested in a time period and then field managers use this as a guide for implementation. This pattern appears to have begun as early as the mid 1500s with the development and publication of a model for forest management in a forest management text. That model is a "normal forest" which contains three components:

1. A normal (or even) distribution of age classes;
2. Normal stocking in each stand; and
3. Normal growth for the Forest as a whole.

This model describes a forest condition/dynamic equilibrium state that if achieved and maintained through time will yield a maximum, sustained flow of sawtimber. It was developed as a model for management of forests in order to meet needs of society for sustained production of wood products.

As foresters armed themselves with this model or goal, they went out to manage forest lands. In every case, the lands they came to manage were not organized/regulated to match the condition defined as a normal forest. So they had to develop a management scheme and guides to move a forest from its current condition toward the desired condition.

Development of a management scheme and guides appears to have been split into two distinct pieces. One piece focussed on the second and third parts of the "normal forest" description and developed silvicultural guides for stocking control as well as normal volume and yield tables. A second group concentrated on developing procedures/analysis techniques to guide movement toward and then maintenance of an even distribution of age classes. This second problem is often referred to as calculation of the allowable cut or now, in the U.S. Forest Service, calculation of an allowable sale quantity (ASQ).

Application of results of these two parts of the problem appears to have been accomplished in two sequential steps. First, the timber planner/analyst calculates an ASQ for a forest. This ASQ then becomes a guide (and more recently a target) for field managers. The task of the field manager is to identify stands to be harvested that will meet the ASQ. Guidance for this selection is provided by silvicultural guides for stocking control and biological growth of stands (i.e., from volume and yield tables/models and field inspection, the field manager can identify which stands "need" treatment the most and concentrate on those stands for production of the ASQ).

This splitting of the problem of achieving a normal forest into two parts has a number of implications. First, it allowed development of specialized skills and techniques for each part. In other words, some could concentrate on improving estimation of ASQs while others concentrated on techniques for identifying stands "ripe" for treatment as well as harvest design or layout. A problem that can and has arisen is that there is often a conflict between the calculated ASQ volume and the amount that "should" be harvested from a strict silvicultural standpoint.

Secondly, this splitting of the problem appears compatible with a mixed scanning approach to planning and management. When faced with a complex problem, a mixed scanning approach calls for a "high" level decision for guidance of management; e.g., calculation of an ASQ. In this decision making, not all complexities of the problem need to be addressed; e.g., there is not a need to have detailed stand by stand information. Rather, such detail is assumed to come to play during implementation of the decision. In other words, field managers take into consideration the conditions of candidate stands for harvest and attempt to meet the ASQ in a feasible way based on this more specific information. Whether or not application of mixed scanning was a conscious decision, this approach appears to describe traditional modes of operation in timber management.

Third, because the problem was split in terms of specialized knowledge as well as between forestwide ASQ calculations and implementation through application of a mixed scanning approach, those involved in calculation of ASQs could easily overlook questions of how their solutions would be implemented. Calculation of an ASQ is not an easy task. Each stand on a forest has a unique mix of location, cover type, age, site productivity, possible response to silvicultural practices, and stand condition. Because there are literally thousands of stands on any forest, detail on each stand would overwhelm any attempt at calculating an ASQ. When faced with overwhelming detail and complexity, a good analysis rule is to develop simplifying assumptions, estimate a solution, attempt implementation, and then modify the solution through time as necessary because of problems of implementation. A major simplifying assumption that appears to have been accepted in most, if not all, procedures for calculation of an ASQ is to ignore questions of how the solution will be implemented or even if it can be implemented.

Calculation of an Allowable Harvest Level/Allowable Sale Quantity

Simplification of the problem for calculation of an allowable sale quantity has taken on a number of forms over the last 400 years. Up until the last 30 to 40 years, such calculations were done through application of simplified formulas referred to as "area methods" or "volume methods" (Davis 1954, Iverson and Alston 1986). These relied on use of forestwide information including such items as total number of timbered acres, rotation age, and/or estimates of inventory and annual growth. The hypothesis that these rely on simplified assumptions and their results merely estimations appears born out by the fact that no two of these methods will provide the same answer for the same forest. In times where there is at least a perceived shortage of timber volume; when estimates are used as "hard targets" for performance measures of forest managers; where there is a perceived need for tieing budgets and accounting of those budgets in terms of production; and/or when there are other considerations (such as road construction or multiple-use production considerations), such crude estimates of an ASQ is at least perceived as less than satisfactory.

Over the past 30 to 40 years, there have been attempts at developing more precise and/or accurate estimates of an ASQ. This has not been without controversy and in fact some of these efforts appear to have been made in response to controversy. A major point of this paper is that these efforts have focussed almost exclusively on how to become more efficient/precise in calculation of an ASQ and have continued the trend of ignoring problems related to implementation. Further, this result was not based on a conscious decision, but rather is the result of attempting to efficiently resolve a selected part of a problem in context of an assumed historic mixed scanning mode of operation. And finally, the assumption that solutions can be implemented results in analyses procedures which are inappropriate for accomplishing timber analyses supporting Forest Plans for National Forests.

A precursor to linear programming models for calculation of an ASQ appears to have been a procedure referred to as a "tabular method" (Davis 1954). The simplifying assumption of a tabular method is that an ASQ can be calculated using information represented by forestwide timber strata. Each strata is assumed to be homogeneous in terms of cover type, age, productivity, and perhaps response to silvicultural treatments. These strata can then be listed on a spreadsheet by age class for a forest. The timber planner/analyst projects volume and growth by strata by time period (normally a decade), as well as identifies the number of acres of particular strata that would be harvested in each decade. Guidance for which strata to harvest is based on silvicultural considerations, as well as the need to move toward the desired age class distribution described by the normal forest model. Total harvest volumes are tabulated for each decade and compared with those from preceding decades in an attempt to move toward the desired age class while producing a non-declining flow of volume.

Calculation of an ASQ in this manner is labor intensive and may require months of work. Once a schedule has been calculated in this manner, the timber planner/analyst is probably not interested in attempting calculation of other possible schedules to identify which will produce the highest first decade harvest; it was hard enough just to identify one viable solution. In other words, though this method may be more accurate than application of earlier simple formulas, it may be no more precise.

Hidden within these calculations are two conflicting assumptions, both dealing with implementation. First, in order for the calculations of ASQ to be valid, it must be assumed that harvest amounts by acres of specific strata as identified in the solution are possible and will occur. Turning that around, the ASQ was calculated based on a harvest pattern by decade by strata. Variation from this pattern will violate the basis of such calculations and in this way invalidate the volume projections for all decades included in calculation of the ASQ.

The second assumption implicit in these calculations relates to the fragmentation of the timber management problem and at least defacto acceptance of a mixed scanning approach to planning and management. This assumption is that the solution represents an ESTIMATE for guiding implementation, but that it is only a guide. Further, that it is the role of the field manager to use this as a guide as she/he also adds the specifics of candidate stands, transportation networks, efficiency of harvest layout, and any other important considerations such as those related to multiple-use production. Because the harvest pattern underlying the ASQ is perceived as an estimate, stands selected for harvest will probably not match the treatment of acres by strata on which the ASQ calculations are based. This, in effect, means that implementation invalidates the calculations that such implementation are based upon. In other words, unless a forest is already arranged as a normal forest with stands concentrated enough for viable/efficient harvests yet dispersed enough to meet other considerations, the two assumptions on which ASQ calculations are based are in conflict. Thereby, the solution so generated is valid only in a very narrow sense.

Enter linear programming (LP). Over the last 20 years, linear programming based analysis systems have been developed to aid estimation of an ASQ and harvest schedule (for example, see documentation in Iverson and Alston 1986). Though there are significant differences between "Timber Ram," "MUSCY," and versions of "FORPLAN," all but perhaps Version 2 of FORPLAN appear to have adopted the same simplifying assumptions of tabular methods. Included in this is the use of timber strata or in more up-to-date terms, homogeneous, non-contiguous analysis areas. (This is not just a feature of analysis systems developed for "timber harvest scheduling" and is found in most linear programming based analysis systems applied to various aspects of forest management.)

What took months to accomplish by tabular methods could be accomplished in a manner of a single "run" of a LP model (Kent 1980 presents a basic primer on use of LP models). Further, within LP models there is the ability to alter the objective function as well as add or delete constraints. This means that the analyst/timber planner can use such models to answer questions such as the maximum theoretical first decade harvest under a non-declining flow constraint or alternatively, an ASQ and schedule that would maximize some measure of economic efficiency. In short, such LP models appeared to provide unparalleled flexibility for an analysis as well as the ability to calculate "optimum" solutions with more precision.

A question at this point is: are solutions so generated optimum? The only response that can be given from an operations research standpoint is: "yes, they are optimum solutions for the problem as defined (ORAs learn early to weasel word such answers)." However, because these models and approved methods for their use (as presented in users guides) did not alter the basic assumptions included in tabular methods as discussed above, solutions from these models can be no more (or less) valid than solutions from tabular methods. Which in turn means that such solutions are optimal but probably not valid in a broader context of providing solutions that can be implemented to resolve forest/timber management problems. (In fact, such solutions may be very misleading.)

A New Problem for Analysts or a New Perspective on the Original Problem

Implementation of solutions from simple equations up through linear programming models has been a problem facing forest managers since such calculations were begun. Though this has been a problem, it did not become a critical problem requiring attention until the last 30 years or so as questions of scarcity and/or inappropriate results from implementation became a concern of society at large. During this time period, controversy has been a constant companion of timber management within the U.S. Forest Service. Though there have been a number of responses such as altering how and which silvicultural practices are applied where, it appears these are treating a symptom of the problem and not the cause of the problem. In their discussion of the genesis of FORPLAN, Iverson and Alston (1986) point out how LP models have evolved in an attempt to address controversies and provide "better" solutions. This has been an extraordinary evolution in analysis procedures and it appears analysis is catching up on the problem. But perhaps we should not be focussing just on the capabilities of analysis systems, but rather on better definition of the problem to be resolved and more appropriate procedures for use of these analysis systems.

The intent of procedures to calculate an ASQ for a forest is to provide information to a forest manager that will assist in meeting society's needs through management actions on that forest. Through time, this intent became clouded as those involved narrowed their focus on more efficient and precise ways to estimate an ASQ. Efficiency can easily be translated into maximization, so the effort to improve ASQ calculations naturally moved toward calculation of a maximum theoretical yield. Solutions are theoretical because of the simplifying assumptions necessary for calculations. Since the creation of the U.S. Forest Service, though, management has focused, at least philosophically, on provision of "multiple-use" mixes of goods and services that can be produced from a Forest in an attempt to meet society's needs for these goods and services. This was explicitly stated in the Multiple Use, Sustained Yield Act of 1960. Further, within the National Forest Management Act of 1976 (NFMA), this appears to have become the focus of Forest Planning and analysis supporting such planning. As such, the problem facing timber analysis has been and is not just to estimate the theoretical maximum timber yield or even to arrange a Forest as a normal forest to produce a maximum sustained yield of timber, but to arrange it to produce a sustained yield of a particular mix of goods and services.

One reading of the NFMA and its implementing regulations (36 CFR 219) illustrates/supports this point by requiring as part of timber analyses supporting Forest Plans analysis that includes:

> calculation of an allowable sale quantity and base sale schedule;
>
> detailed accounting of costs, benefits (including multiple-use benefits), and environmental effects of proposed timber harvests included within the allowable sale quantity;
>
> assurances that the optimal silvicultural practices will be applied to specific timber strata as shown in the linear programming solution; and
>
> assurance that solutions can be implemented in a viable manner.

This problem may include calculation of theoretical maximums, but it also appears to require detailed, almost site-specific analysis, in order to estimate costs, environmental effects, and solutions that can be "laid-on-the-ground" almost directly. In other words, this "new" problem statement appears to require that the conflict of assumptions imbedded in earlier analysis procedures regarding implementation be resolved; i.e., that mixed scanning approach relying on analysis using simplified assumptions is no longer reasonable. Further, that the focus of analysis procedures is to generate valid solutions rather than theoretical optimal solutions.

Recognition that there may be a new or different problem to be resolved in timber analysis does not appear to be widely accepted nor does there appear to be agreement on the nature of this new problem (Alston and Iverson 1987). This complicates discussions at forums, such as this conference, where those involved in analysis as well as design of analysis tools discuss the relative merits of various models and analysis techniques. While some are discussing different techniques or enhancements to resolve the former problem more efficiently, others appear to be struggling at understanding how to use the existing tools to solve the more involved problems facing Forest Planning.

Implications and Possible Solutions in Forest Planning

There appear to be three general strategies that can/have been used to resolve this new problem while utilizing analysis tools that were developed to solve the old problem. Briefly, these are:

1. Ignore the problem. Under this strategy, the difference between the two problems is/was probably not recognized by management (some in the public may recognize it, though). In these cases, it is quite common to deal with implementation as a separate problem from planning. In other words, FORPLAN is used to calculate an allowable sale quantity and to accomplish required timber analysis and justification following standard solution procedures (i.e., solve the old problem). This is the province of the forest planners and operations research analysts. Implementation, however, is viewed as a problem separate from development of the Plan.

Implementation of solutions from timber analysis portions of a Forest Plan becomes the responsibility of the timber staff officer and forest silviculturist. Following the traditional approach to implement results of timber harvest scheduling analysis, they use the bottom line volume calculated for the allowable sale quantity as a target to be achieved in timber sales. Timber sales are then planned so that they "fit" the ground in a viable way to produce the desired volume. The harvests by strata identified in the FORPLAN solutions often are not consulted in this on-the-ground layout of sales. Because planning and implementation are separate activities in different parts of an organization, there is probably little if any recognition that there is a problem between the two.

2. Post analysis recognition of the problem. Under this strategy, FORPLAN is used to solve the old problem as in approach 1. However, there is at least a partial recognition that the solution from this analysis supporting a Forest Plan may not be a complete solution to the new problem that was to be resolved in that Forest Plan. Based on this, there is a perceived need to augment the basic analysis supporting a Forest Plan during implementation. This is accomplished through such procedures as Integrated Resource Management or area analysis. These represent attempts to "lay-on-the-ground" a sequenced and integrated set of projects that attempt to achieve both the volumes/acres of treatment and schedules over time by strata called for in analysis. Also such processes address achievement of such items as desired forest conditions, multiple-use production concerns, and environmental consequences on a more site specific manner. In this way, the accounting of costs, benefits, multiple-use production effects and other environmental effects are estimated. In this procedure, mixed scanning is appropriate because the Forest Plan is used as a guide that can be altered based on site specific considerations; i.e., flexibility is provided in this approach for field managers to resolve inherent conflicts caused by assumptions within analysis and amend the Forest Plan when necessary. This approach appears to have a number of advantages over the first approach including the ability to resolve/address the new problem. It is probably the best that can be accomplished given current understanding of problems associated with planning.

3. Pre-analysis recognition of the problem. Under this strategy, at least some of the differences between solutions generated through standard formulations of timber harvest scheduling models and that required to resolve the new problem facing timber analysis in Forest Planning are recognized prior to formulation of an analysis process. The analysis process and formulation of a FORPLAN model are then structured to resolve this new problem. This includes attempting many of the analysis tasks being performed during implementation in approach 2 as part of Forest Planning analysis and entering such information into FORPLAN.

Approach 1 appears a continuation of the way timber analysis and implementation have been accomplished traditionally. It has advantages in terms of simplicity of analysis models and the ability to meet targets assigned as a result of that analysis. Further, because it follows traditional patterns of planning and implementation, there will be little disruption or change from an organizational standpoint. It does not provide a method for addressing/ resolving the new analysis problem and can easily keep forest managers center stage in controversy. Because of this, it may have some significant short-comings; least of which is the validity (or lack) of its "optimal" solutions.

Approach 2 is well documented elsewhere (e.g., Eastern Region, U.S. Forest Service 1985). It appears that the common procedure for formulating a FORPLAN model under this approach is about the same as that in approach 1. That is, timber is modeled much as it would have been under a tabular method for calculation of allowable sale quantities. This includes forestwide homogeneous, non-contiguous analysis areas. Coefficients within FORPLAN represent per acre results of applying a specific prescription (sequence of practices)/timing option to one acre of an analysis area.

Once such a model is constructed, it is used to accomplish timber analysis required for Forest Planning (see 36 CFR 219 and national analysis standards for a discussion of required analysis). Solutions include a listing of the acres to be treated by decade for each strata; and if geographic breakdowns were included within the model, an estimate of acres treated by strata by geographic area. Such solutions are used as analysis support for Forest Plans. However, published Forest Plans normally do not include detail on the amount of treatment expected to occur by geographic area through time. Rather, Forest Plans indicate general management intent by geographic area.

During implementation under approach 2, the Forest is subdivided into geographic areas (sometimes referred to as opportunity areas). The general management direction or directions for that area as published in the Plan are noted and an interdisciplinary team assembled. At this point, attention turns from forestwide considerations and FORPLAN modeling to analysis/identification of projects that could be implemented within this specific area. The focus of this effort is to identify and analyze alternative sets of projects (practices plus standards for application of those practices) that could achieve the general management intent(s) selected for that area in the Forest Plan. During this effort, the FORPLAN solution supporting the Forest Plan may be consulted to identify acres of treatment by strata as a guide. But because strata are normally forestwide in nature, it

may be difficult to track whether projects analyzed for each geographic area will achieve the treatments included in the Plan. Such tracking is further complicated by such common procedures as having different interdisciplinary teams (perhaps one team on each District) working on analysis for subdistrict geographic areas. Also, complete tracking can not occur until all such area analysis is completed. Given that analysis for a single area may require up to 6 months of work and that there may be as many as 80 to 100 areas on a Forest, it could take several years worth of work to complete such analysis.

From an analysis standpoint, the final result (after area analysis is complete) of this staging of analysis can result in near total accounting of costs, benefits, and environmental effects. In this procedure, the general, per acre coefficients in FORPLAN can become much more site-specific through analysis supporting implementation. Through project identification, types, location, and sequencing of timber treatments can be identified. This, in turn, provides information on the overall forest condition that will be created through implementation on a specific area of the forest. This estimate, in turn, can provide a basis for estimating resulting levels of production of those items which have a strong spatial component in their production functions such as wildlife habitat, visual quality, recreation opportunities, impacts on soil and water, transportation networks, and such timber related considerations as integrated insect and disease control and regeneration considerations.

In short, approach 2 appears to utilize FORPLAN and other forestwide analyses to identify general direction for various parts of a Forest. Based on these broad decisions, separate, area-by-area analyses attempt to identify specific projects that both meet the general direction established in the Plan as well as site specific considerations toward achieving some type of desired forest condition, at least in each specific area. In this manner, analysis turns to identification of a possible set of superior solutions and allows "decision-makers" the latitude of selecting among a set of superior solutions. In other words, analysis moves out of a search for a theoretical "optimum" toward the realm of the practical/implementation solutions for problems facing management. This system appears to work fairly well and does appear to provide a mechanism for capturing the multiple-use production inherent in forested ecosystems. Some questions raised by this approach, though, include:

> What is the role of the original FORPLAN solutions?
>
> Because tracking between those solutions and results of area analysis is difficult, what was the real value of using FORPLAN? Was it merely to address some policy questions such as the relative merits of harvest prior to culmination of mean annual increment or departures from even flow?
>
> If these are the questions that FORPLAN/linear programming was to answer, is there a need for a complex and expensive linear programing model or would something simpler, less costly and less time consuming have been adequate?
>
> If site specifics of multiple-use production as well as associated costs such as those for a transportation network are dealt with in subsequent area analysis, how "optimum" are solutions from a FORPLAN model?
>
> If analysis during implementation is done on an area by area method over a fairly long time span, are resulting "solutions" optimal from a forestwide perspective?

With those questions in mind, let us turn our attention on the third approach. A basic assumption underlying this approach is the hypothesis that if it is possible to deal with site-specific considerations for timber analysis through area analysis subsequent to FORPLAN analysis, then it should be possible to deal with these prior to FORPLAN analysis and include them in a FORPLAN model. This sounds simple enough, but requires an alteration in the conceptual basis of constructing a linear programming model for calculation of allowable sale quantities.

Construction of a linear programming model for calculation of an allowable sale quantity often includes:

> forestwide timber strata/analysis areas--timber stands scattered across a forest that are assumed to be homogeneous in terms of response to practices that could be applied to them. This often includes homogeneity of cover type, age class, site productivity, and slope class as well as perhaps such items as soil stability, broad accessibility class, and/or within areas of high sensitivity from a visual or hydrological standpoint.
>
> prescriptions--a set of sequenced practices that could be applied to an analysis area.
>
> costs, effects, and yields--an estimate of these items that will be incurred/produced if/when a prescription is applied to a single acre of the appropriate analysis area. These become coefficients within a linear program.

Construction of such a model, estimates of costs, effects and yields, and analysis using such a model assumes a straight-line, cause and effect relationship between application of a prescription to an analysis area; that is there is a one-to-one relationship assumed between application of a specific practice to an acre of an analysis area and the results estimated as coefficients within the model. Because analysis areas/timber strata are forestwide in nature, this can only be true in a very narrow sense--perhaps only in rough estimates of timber volume to be produced and general economic concerns. Further, unless there is flexibility to alter solutions generated through analysis during implementation, there is a high probability that such results are not implementation and therefore invalid.

In order to improve the probability of solution validity, approach 3 requires a different assumption regarding the relationship between practices and production functions of forest ecosystems. (As will be discussed later, it also requires a

different method for formulating analysis models.) This different assumption is that production of goods and services including timber is a function of how sets of practices applied over time and space alter the condition or state of a forest ecosystem or set of ecosystems within a specific area. In other words, costs, benefits, environmental effects, and multiple use production levels are assumed to be a function of ecosystem states. The role of practices, then, is one of altering the current state. This means that estimation of results of applying a specific practice to a specific area requires an estimation of:

> how much of that practice is applied (e.g., how many acres are harvested);
>
> the standards/management requirements/design criteria that will govern application of that practice; and
>
> what other practices are going to be applied prior to, simultaneously, and subsequent to that practice within the same general area (say over a 5,000 to 40,000 acre area) and the standards/design criteria for those practices.

There are a number of ways this third approach can be classified or characterized. Some find it crazy, others find it arrogant, and some dismiss it as "a stupid way to build a model." A more useful way to classify it is that it represents an incremental change within a context of a mixed scanning approach to planning. A mixed scanning approach to planning is represented by approach 2. It could be viewed that all approach 3 does is take the output of approach 2 in terms of alternative mixes of feasible projects that could be applied to an area on a Forest and feeds these into a model for further analysis. The purpose of this further analysis is to identify, based on a look at feasibility and the full set of costs, effects, and production levels, which alternative for each area of the Forest is necessary to efficiently meet forestwide goals and objectives. As such, approach 3 could be considered nothing more (or less) than a final step for completing analysis under approach 2.

One other way that approach 3 can be characterized is as a "systems approach" to planning. Management of a forest is viewed as manipulation of a set of systems (some refer to it as a set of ecosystems). These systems are interacting with each other and with their environment and through this interaction are producing a mix of goods and services. The specific mix of goods and services is defined by the configuration of these systems. In theory, if the mix being produced is not a desired mix in terms of meeting society's needs, then the role of management is to alter the configuration of these systems so that the desired mix of multiple-use goods and services can be produced. (To some, this is little more than a site specific extension of the concept of a normal forest and using that to guide all management activities on a forest.)

Analysis under a systems approach, begins by identifying the current condition of involved systems through such measures as age class distribution, spatial arrangement of habitat components, edge, diversity measures, and/or open road densities of specific, geographic areas on a Forest. A second step, based on problems facing management, is to identify ecosystem states that if achieved on those areas would produce desired mixes of goods and services. A third step, is to identify a mix of practices and associated standards/design criteria for those practices (i.e., a mix of projects) that could be applied to an area to alter its current condition so that it matches one of the desired ecosystem states. Each mix of projects can be considered a "prescription" for that area. Specific consideration of such items as spatial arrangements, age classes, edge, vegetative diversity, desired recreation opportunities, and road densities are included WITHIN these prescriptions. Because there are a multitude of possible ecosystems states that could be achieved in a specific area as well as a multitude of ways to achieve and maintain these states, FORPLAN analysis focuses on sorting through these possibilities to identify not only the mix of ecosystem states that are desired, but specific ways in which this will be accomplished. Results from FORPLAN analyses will thereby be an identification of projects for specific areas on a Forest. In effect, results will be almost identical to results generated through full application of approach 2 including the area analysis done during the Plan implementation phase in approach 2.

(Note/aside--some early proponents of something similar to approach 3 suggested that a first stage of analysis focus on selection of desired forest conditions for various areas of a forest. Once this selection is complete, use this selection as a constraint or set of constraints on a "scheduling" model. This was simplified and classified as a two stage process and rejected by majority of "analysts" in preference to "basic, simultaneous allocation, and scheduling." Though approach 3 may rely on some of the basic concepts of a two stage approach, it is really is much more a modification of a basic simultaneous allocation and scheduling approach.)

Though the final results of approaches 2 and 3 look very much alike, there are significant differences in: potential validity of analysis solutions; when and how "site-specific" analysis is accomplished; how decisions reached on specific areas of a Forest influence and are influenced by forestwide considerations; the time involved in reaching those results; ability to involve the public in a meaningful way prior to completion of a Forest Plan; ability to track solutions from FORPLAN to actual projects on the ground; ability to accomplish cumulative effects analysis in Forest Planning detailed enough for tiering project level environmental analyses; and providing information from FORPLAN that is useful for structuring budget proposals as well as allocation of budgets and "targets" to Ranger Districts. In all of these areas, approach 3 has the potential for significant advantages over approach 2. Before basking in thoughts of how far superior approach 3 is though, a question of some import is whether approach 3 is possible.

A Test of Approach 3

In 1982, the Shoshone National Forest initiated an attempt to implement approach 3. The Regional Office had given the Shoshone a charter to use and test Version 2 FORPLAN as well.

This means that not only was this a test of approach 3, but it was a test of whether approach 3 could be implemented using a currently available analysis system.

The focus of this effort was to create a detailed, nearly site-specific Forest Plan while meeting all Forest Planning analysis requirements. This focus on site specificity was chosen in an attempt to assure solution feasibility as well as deal with multiple-use considerations of timber management activities in what appeared to be a more reasonable manner. This effort required use of three separate, but linked, sets of analyses with each set of analyses requiring a FORPLAN model (Mitchell 1986, Mitchell et al. 1985). The most dramatic differences in these models and normally found are in the third and final model used for analysis, particularly those portions of the model related to timber analysis. The following discussion concentrates on this final model and how it was structured to accomplish required analysis related to timber.

(Version 2 FORPLAN was used for all three models. The following discussion uses terms specific to this analysis system. Those unfamiliar with V2 FORPLAN should refer to V2 FORPLAN User's and/or Programmers Guides or such publications as Mitchell and Kent 1986.)

Before FORPLAN modeling began, the Forest interdisciplinary planning team (ID team) examined problems facing management of the Forest (in Forest Planning jargon, they examined issues, concerns, and opportunities). The focus of this examination was to identify/design specific ecosystem states that if achieved and maintained, would result in sustained yield of a multiple-use mix of goods and services in response to each problem. These ecosystem states were referred to as Shoshone Management Goals [based on the definition of a goal within the Forest Planning regulations (36 CFR 219.3)]. Each goal for timbered ecosystems contained such information as a desired age class distribution/structural stages, desired size of canopy breaks (e.g., 5 to 10 acre clear cut patches for water flow enhancement or 26.5 acre openings for elk habitat improvement), total road density, open road density, and visual quality objectives. The level of specificity included was dictated by the level of specificity necessary for each specialist to estimate multiple-use production levels that would result from achievement of such ecosystem states.

Identification/design of Shoshone Management Goals was done for two separate reasons from an analysis standpoint; both dealing with standards/management requirements/design criteria. First, within analysis requirements for Forest Planning, there is a requirement to analyze "opportunity costs" and relative cost efficiency of standards that are felt necessary for production of goods and services other than timber. This analysis requirement appears to stem from use of "constraints" within a linear programming model which are justified as necessary in order to meet "minimum management requirements" or other desired levels of multiple-use production. In more conventional model formulations, such "constraints" are common as a means for representing management standards. Identifying opportunity costs of such constraints is relatively easy by making "paired" runs of the linear program model--one with a constraint(s) and one without--and then comparing results.

In order to apply approach 3, it is necessary to include standards within each prescription. Such standards are necessary because of the assumption that production is a function of forest conditions. In other words, in order to estimate costs, benefits, multiple-use production levels, and environmental effects, it is necessary to identify what forest conditions will result from application of practices to specific areas on the Forest. This means that a linear program model used in approach 3 does not utilize constraints to represent standards, rather they are included within prescriptions so that estimates of effects and production levels can be made. If standards are included within prescriptions rather than as constraints, analysis of opportunity costs using "paired" runs is not possible. What is possible is to build a model which includes alternative prescriptions, each with a different set of standards. Using such a model, it is possible to analyze differences in production levels and economic measures generated by different sets of standards. In this way, it is possible to identify the most cost efficient set of standards. It also is possible to analyze "opportunity costs" between these and "unconstrained" prescriptions.

Unconstrained in approach 3 takes on a different meaning than in more conventional modeling. Part of this difference relates to how analysis models are formulated as discussed. Another part of the differences relates to the basic assumptions underling estimates of production; i.e., in order to make such estimates, a "systems approach" requires identification of the anticipated forest condition that would result from implementation of practices included in a prescription, which in turn requires identification of standards that will be used to guide implementation of practices. Thus "unconstrained" really means identification of different sets of less restrictive standards than that necessary for meeting multiple-use management requirements; e.g., allowing harvest blocks to have straight edges and cover areas as large as several hundred acres at a time.

This highlights a basic difference between approach 3, other approaches, and standard modeling as done using such tools as Timber Ram and MUSYC. All but approach 3 assume that it is possible to capture multiple-use and environmental effects just by knowing that a practice is going to be applied to a single acre of a forestwide timber strata regardless of where that acre is on the forest, standards that will guide application of that practice, and what practices are being applied to adjoining areas. That is what is included as coefficients in a linear programming model. In approach 2, this assumption is altered slightly to become: it is possible to capture enough of these effects within a linear programming model to make a reasoned decision on an alternative, but final accounting of these will not occur until "area analysis" is done. In area analysis, it will be possible to examine what practices are going to be applied and their spatial and temporal relationships on a specific area.

The assumption underling approach 3 is that it is not possible to estimate multiple-use and environmental effects just by knowing that a practice will be applied to a single acre of land

at a specific point in time. This point appears to be a major conceptual difference among many who have been involved with National Forest Planning. (This difference in basic assumptions is rarely discussed or acknowledged. Because of a lack of recognition of this difference, discussions between people with different perceptions focus on "modeling" techniques and why a particular enhancement may be needed. These discussions have often been heated and no conclusions reached because of a lack of understanding and discussion of differences in basic assumptions.)

A second reason for identifying desired forest conditions (Goals) prior to analysis is to provide direction for construction of prescriptions. Treatment of timber stands including harvest of that timber can and does have effects on production of other goods and services as well as environmental effects. Before such harvest or other treatment is done in the field, alternative ways of doing this are normally investigated in an environmental analysis. At this stage, an interdisciplinary team is normally involved in design of application of treatments and often include consideration of "optimizing" multiple-use production effects of these treatments. In approach 3, such ID team deliberations and design considerations are to be explicitly included within prescriptions. In order to do this, it is necessary for an ID team to identify how such treatments and harvests could be applied to "optimize" production of one or more multiple-use mixes of goods and services. This is the type of design included in development of Goals which results in identification of alternative sets of standards for application of practices. This in turn, provides information necessary for estimating costs, benefits, and effects of prescriptions to be included within a linear programming model.

Formulating a linear programming model to implement approach 3 requires dealing with two opposing types of considerations. On one hand, there is a need for "site specificity" in analysis, including specification of both spatial and temporal sequence of activities to be implemented within a geographic area. On the other hand, analysis should include a "wide range" of timing choices for activities in order to deal with such issues as non-declining timber flows and investigation of maximum production possibilities through time. Version 2 (V2) FORPLAN is a powerful and flexible analysis system which provides many alternative methods for modeling about anything of interest, but particularly timber. Most of these methods were investigated by those involved with planning on the Shoshone National Forest as ways to achieve the specificity necessary for approach 3 as well as generation of a wide range of timing choices necessary to accomplish required analysis. Some of these options provided either the necessary specificity or the flexibility, but not both. Therefore, it was necessary to build a "composite" model which combined available options, as well as utilized a slightly different definition of "prescriptions" than that used in conventional modeling. [Discussion of this difficulty and other attempts to resolve it is presented by Iverson and Alston (1986) in terms of "enhancements" in both versions of FORPLAN.]

In order to deal with these two considerations, two ways of representing analysis area information were combined. This included linking heterogeneous, contiguous analysis areas with "allocation scheduling zones" containing homogeneous, noncontiguous analysis areas. Prescriptions for these combined analysis areas could also be considered "compound" prescriptions. Such prescriptions were combinations of "Directly Entered" prescriptions and "Themed" prescriptions and again were linked to form a single set of choices within the model. (Hopefully, that set of sentences can be translated into something approximating common parlance in an understandable manner.)

In order to define a set of analysis areas, the Forest was subdivided into 109 geographic areas. Each of these are large enough to deal in a reasonable way with transportation networks (including trails), watershed considerations, habitat or migration routes for wildlife, recreation and visual considerations, and diversity. These areas were then represented in the model in two different ways. First, all of the land within the boundary of a geographic area, except that which had been defined as tentatively suited timber land, was modeled as a contiguous, heterogeneous analysis area. (Some of these analysis areas were entirely within classified wilderness areas, so all land within the boundary was included in such analysis areas.) For each of these contiguous, heterogeneous analysis areas that had tentatively suited timber land within their boundary, an allocation schedule zone was created. Outside boundaries for each allocation schedule zone matched the boundary of its associated geographic analysis area.

Tentatively suited timber land within the boundary of an allocation schedule zone were then represented as homogeneous, noncontiguous analysis areas. Even though these analysis areas were confined to specific geographic areas on the Forest (i.e., they were not forestwide strata), the definition of these are the same or similar to timber strata used in conventional models; i.e., each such analysis area was homogeneous in terms of cover type, age class, possible cover types, productivity, and response to silvicultural practices. In effect, an allocation schedule zone was nothing more than a collection or set of all timber strata within its boundary with each strata retaining its own identity. This grouping into zones was done for two reasons. First, to provide a mechanism for coordinating activities within a specific area through use of another V2 FORPLAN feature referred to as coordinated allocation and scheduling choices. Secondly, to provide capability for using FORPLAN reports to identify the specific activities/prescriptions selected for each geographic area on the Forest.

Prescriptions within the FORPLAN model represented a mix of practices and associated standards. Identification of practices and standards to be included within prescriptions was based on descriptions of desired forest conditions/ecosystem states. For example, a possible desired state for timbered areas along a migration route for elk is to have a portion of that area in 26.5 acre openings that are surrounded by cover. Given this, at least one of the prescriptions included within FORPLAN for

such areas included appropriate harvest practices that will be implemented under a set of standards that limit size of openings to 26.5 acres and dispersion of harvest blocks over time and space in order to provide cover surrounding these openings. Standards for all practices including such things as road construction, transportation network management, range management, trails, and wildlife habitat improvements as needed to achieve designed (not necessarily selected) ecosystem states were also included within prescriptions.

In this attempt to implement approach 3, the word "prescription" takes on a meaning different than that normally used in conventional modeling, particularly for geographic areas containing tentatively suited timber land. In conventional modeling a prescription is a set of practices that can be applied to a single acre of an analysis area. Coefficients within such models represent only those effects which can be estimated on a per acre basis. In the Shoshone's attempt at approach 3, a prescription is a coordinated set of projects (practices and standards) to be applied to a specific area in a specific sequence. Coefficients within the model represent the estimated combined effects of applying those projects to that area, including effects that have strong spatial components within their production functions (e.g., useable wildlife habitat). In this way, the ID team could model solutions to site-specific management problems on a geographic area by geographic area basis. In order to do this while still providing a wide range of timing choices (particularly for timber), "prescriptions" for areas containing tentatively suited timber land had three components. In other words, it is not possible to examine a single portion of the input data to identify what is included within a single prescription.

Prescriptions for those areas which did not contain tentatively suited timber land were "directly entered" prescriptions. Use of directly entered prescriptions is a unique feature of V2 FORPLAN and allows specification of the amount of each practice, cost, effect, output, and benefit anticipated through time for a specific prescription for a specific analysis area. In effect, a directly entered prescription is little more than a column in the resulting linear program matrix. For these areas, the ID team working with field personnel, identified various sets of projects which could be implemented within these areas to address both site-specific and forestwide management problems. Each set of projects covered a span of at least 100 years as did estimates of goods, services and environmental effects. For these analysis areas, prescriptions were "straight-up" application of the direct entry option in V2 FORPLAN.

For those geographic areas which contained tentatively suited timberland, prescriptions were disaggregated into three linked parts. The first part was a directly entered prescription. This represented a coordinated and sequenced set of projects (practices and standards) necessary to alter the current condition of all but the tentatively suited timberland within a geographic area toward achievement of a specific mix of ecosystem states in response to both site-specific and forestwide management problems. These directly entered prescriptions were similar to those developed for areas that did not have tentatively suited timber land. As such, these prescriptions included estimates of the costs, output levels, benefits, and effects that would result from implementation of those projects. This included such items as the amount and timing of arterial and collector roads necessary to support the overall intent of a prescription. Estimates of effects and/or output levels included within these prescriptions were based on a specific mix of projects including their spatial and temporal relationships.

The second part of a prescription for those geographic areas containing tentatively suited timber was represented as a Coordinated Allocation and Scheduling Choice for the appropriate Allocation Scheduling Zone. As stated earlier, all of the timber strata within a geographic area were collected as a set; i.e., within an allocation scheduling zone. One of the options available in V2 FORPLAN when such sets are used, is the ability to identify a set of management options available to strata within that set, as well as do such things as identify when access to various portions of each strata will be available. This is referred to as a Coordinated Allocation and Scheduling Choice (CAC). Using this feature, it is possible to develop a CAC that is coordinated with the directly entered prescription for a geographic area in terms of overall management strategy, as well as such considerations as specific schedules for construction of collector and arterial roads. It is also possible to include estimates of effects, costs, benefits, and output levels that could be produced given this CAC. In order to link a particular coordinated allocation and scheduling choice for a specific allocation scheduling zone with the appropriate directly entered prescription for a geographic area, it was necessary to develop a transfer row through the use of a specific output and set of constraints. This had the effect of making a specific CAC and directly entered prescription appear to be a single option within the resulting FORPLAN model. (As a unanticipated side benefit, this had the result of nearly transforming a linear programming model into an integer programming model.)

What all of that means is that it was possible to link a coordinated set of non-timber projects with a set of compatible timber projects for a specific area on the Forest.

Within a CAC, it is possible to identify the types of prescriptions available for timber strata within the appropriate allocation and scheduling zone. In this way, it was possible to identify which types of timber projects (practices and standards) would be appropriate and compatible with the intent of a particular CAC. These were identified as part of the definition of a CAC. Within sideboards set by such selections of types of timber projects within a CAC, there are a number of possible times when various types of silvicultural treatments could occur on each strata within a geographic area. Which timing choice for how many acres of which strata is most appropriate for producing a forestwide level of timber through time as well as having desired simultaneous multiple-use effects is a major question to be addressed in Forest Planning. In V2 FORPLAN, an option referred to as "theming" can be employed to efficiently generate a full (or at least reasonably full) set of management strategies and timing options for each strata. This option was used here.

Prescriptions that were themed in this effort, however, differed from "timber harvest prescriptions" used in more conventional FORPLAN model formulations. In more conventional models, timber harvest prescriptions include specific practices that could be applied to a single acre within a timber strata and include costs, benefits, and associated multiple-use production effects that can be estimated on an acre-by-acre basis. Unless otherwise constrained, solutions from such formulations can include harvesting an entire strata within a specific time. This may not yield a desired ecosystem state unless all acres of each timber strata are already well arranged spatially and in terms of age class distribution. (If all acres were already well arranged in these terms, solution of the "problem" of estimating an allowable sale quantity and base sale schedule would be a trivial problem.) Given that the approach on the Shoshone was to be a systems approach, a different formulation appeared to be necessary.

This different formulation involved attempting to include within a themed prescription for a timber strata a specific set of standards on such things as: size of openings to be created; amount of the strata that could be harvested at any single time; design standards for harvest block layout; local road densities; management of these roads (e.g., open for public use following harvest operations or not); and other requirements necessary for achieving a desired ecosystem state and its associated multiple-use mix of goods and services. In this manner, specialists on the ID team had some basis for estimating production levels of goods and services which have a strong spatial component within their production functions; e.g., usable wildlife habitat and/or recreation opportunities/use. These estimates as well as estimates of costs of all relevant practices and necessary actions to meet standards included within a prescription were included as part of that prescription for a particular strata. This meant that if the solution assigned all acres of a particular strata to a single timing choice within a "themed prescription," only a specified portion of that strata would be harvested at any one time and harvest of the remaining portions would occur at specific intervals. In this way, it was hoped that harvest scheduling of strata acres from the FORPLAN solution could be placed on the ground in a manner consistent with achieving a specific ecosystem state and in a manner coordinated and consistent with management of surrounding/surrounded non-timbered areas. (A discussion of specifics of how this was accomplished within FORPLAN is beyond the scope of this paper, but can be acquired by contacting the Shoshone National Forest.)

Within the final model used to accomplish analysis supporting the Shoshone Forest Plan, then, is:

a set of analysis areas representing specific geographic areas on the Forest. Acreage of these analysis areas was the total acreage within the area boundary minus acres of tentatively suited timberland.

timber strata representing stands which are homogeneous in terms of cover type, condition of cover type, possible cover types, age class, and response to silvicultural practices as well as all within the same geographic area.

allocation schedule zones with each zone comprised of all tentatively suited timber strata within a specific geographic area.

directly entered prescriptions for the geographic analysis areas that represent a coordinated set of projects (practices and standards) designed to alter the current condition of an area to that described by a specific ecosystem state or set of ecosystem states.

coordinated allocation choices for the allocation schedule zones that specified a set of prescriptions available for timber strata included within a specific zone. Each such choice was linked to the appropriate directly entered prescription for the geographic area that matched the allocation schedule zone boundary.

themed prescriptions for timber strata that included practices and standards necessary for achieving and maintaining a desired ecosystem state through time.

Analysis Using this Model

From this model description, a number of implications/conclusions can be drawn regarding assumptions included in analysis and the type of analysis possible. In more standard timber harvest models, it is assumed that all significant production effects can be captured on a "per acre" basis; that is most of the significant production effects can be estimated if we know what practice is going to be applied to one acre of a particular timber strata. This was an assumption carried over as a simplifying assumption so that tabular methods would be possible. Further, this appears a reasonable assumption if one is attempting to estimate the maximum biological allowable sale quantity and sustained yield level possible. Again, that was one of the questions/part of the problem for which analysis tools such as Timber Ram, MUSYC, and the at least major portions of V1 FORPLAN were developed. If this is the question or at least one of the major questions, then other simplifying assumptions/modeling techniques may be appropriate such as use of forest-wide, non-contiguous, homogeneous analysis areas.

Approach 3, as discussed above, identifies the problem to be resolved differently. That is, calculation of the maximum feasible allowable sale quantity and estimation of the entire range of multiple-use effects that would result from this. Under this approach, it is assumed that simultaneous production of multiple-use goods and services (including timber) occurs on a forest and is a function not only of the practices applied to each acre, but the standards/management requirements guiding such application and how those practices are applied over time and space. In short, it is assumed that significant production effects are related to resulting forest conditions/ ecosystem states rather

than to practices. This approach requires becoming more site specific in terms of analysis areas than in other approaches.

The FORPLAN model formulation described above was an attempt to solve this second problem--that of a "feasible" allowable sale quantity along with associated multiple-use production effects. Because a variety of desired ecosystem states were included in alternative "prescriptions" as well as a full range of timing options for implementation of practices (including silvicultural practices), it was possible to use this final model to investigate a full range of production potentials for all goods and services (benchmark analysis), as well as a full range of Forest Plan alternatives for which there was reasonable assurance of implementability of FORPLAN solutions. Further, it was possible to meet most analysis requirements using this final model.

Analysis requirements that could not be readily met with this final FORPLAN model include:

> calculation of MAXIMUM BIOLOGICAL: allowable sale quantity, base sale schedule, and sustained yield level; and
>
> calculation of "opportunity costs" of meeting dispersion standards.

Because standards on the amount of any single timber strata that could be harvested at any time were included within "prescriptions" in the final model, there was concern that results from the final model would not be deemed sufficient for meeting these analysis requirements. This was one reason for use of more than one model for analysis under this approach. One of the other FORPLAN models used in analysis was a "straight-up" timber harvest scheduling model. This model only included tentatively suited timber lands modeled as forestwide timber strata (homogeneous, noncontiguous analysis areas). Prescriptions included in this model were also "standard" in terms of representing unconstrained application of silvicultural practices that could be applied to each strata. Using this model, alone, it was possible to meet the first set of analysis requirements listed using standard analysis procedures. It was also possible to investigate other analysis questions such as effects or "opportunity" costs (in terms of timber volume) of nondeclining flow considerations and harvest prior to culmination of mean annual increment. Further, by comparing results of this model with results from the final FORPLAN model for similar problem formulations, it was possible to investigate "opportunity costs" of standards included in the final model, including dispersion standards. Timber strata definitions, with the exception of spatial location, were identical between these two models as were the basic timber yield files. This not only provided reasonable assurance that results from the two models were comparable; but made construction of the timber model almost a trivial exercise because all necessary data had already been developed for the final model. (A description of the full set of analyses accomplished using these models as well as results of such analyses can be found in Appendix B of the Environmental Impact Statement supporting the Shoshone Forest Plan.)

Results and Implementation

Using this analysis procedure and the final FORPLAN model resulted in solutions which identified a set of integrated and sequenced (at least by decade) projects for each of the 109 geographic areas. This included identification of the acres by timber strata within each geographic area to be treated each decade and the standards and ecosystem state such treatments should be designed to meet. Such results are basically the same information at approximately the same level of detail as that which would result through full implementation of approach 2. Time and analysis costs for this approach for producing a Forest Plan are probably at the high side of average for Forests implementing approaches 1 or 2. However, in approaches 1 and 2, there is a considerable amount of additional work to be done during implementation in terms of identifying sets of projects necessary to implement Forest Plan direction. Under approach 3, all that remains is "ground-truthing" selected projects. In this way, the ability to move directly into implementation is both simpler and greatly reduced in time, effort, and costs under approach 3.

Once analysis had been completed, reports from FORPLAN were generated on a geographic area by geographic area basis. This provided information for each area that identified:

> the full set of practices to be implemented within the first 10 years on that area (including acres of each timber strata within that area to be treated by specific silvicultural practices);
>
> standards/design criteria for those practices including information on the ecosystem states desired within that area; and
>
> anticipated multiple-use production effects and other anticipated environmental effects of applying those practices under those standards.

This information for the first decade was translated into something approximating common usage English and published on an area by area basis within the Forest Plan. In this way, the public as well as those on the Forest involved in implementation, could easily identify what projects were planned for each area on the Forest. (This appears to have facilitated public review of the Proposed Plan as well as their ability to offer useful information for possible changes between the proposed and final Plan.)

Implementation is a relatively straightforward task. This involves identifying a reasonable sequence for projects selected for each geographic area on a year by year basis (e.g., build the collector road before preparing a timber sale accessed by that road). Then for projects that are to occur early within the first decade, "ground truth" the feasibility of those projects and begin project level, site-specific environmental analysis. And finally, once this environmental analysis is completed for a project, implement that project and monitor results.

Because results from FORPLAN were "site specific," tracking between the solution from FORPLAN and actual projects to

be implemented is almost a trivial problem. However, there remains a measure of discretion and judgment provided for those involved in implementation while keeping implementation consistent with results of FORPLAN analysis. Identifying timber stands to be treated within the first decade is a good example of this. Because standards were included within FORPLAN on the maximum amount of each strata that could be harvested within a geographic area at any one time, there is almost always at least three times as many acres of that strata within a geographic area than that scheduled for treatment in any decade (minor exceptions included application of selection harvest systems and the final stage of shelterwood harvests on stands where such systems were initiated prior to the Forest planning effort). This means that District personnel have an opportunity to map and examine in the field all stands within a strata scheduled for treatment during the first decade within a geographic area. Because there are at least 3 times as many acres of such strata than the number of acres selected for treatment, choices must be made as to which of these candidate stands should be treated (i.e., which stands are going to comprise a timber sale). Criteria for such selections include such items as which stands "need" treatment the most from a silvicultural standpoint, ability to achieve design criteria necessary to achieve the desired ecosystem state (including dispersion standards), necessary construction and location of local (timber hauling) roads, and economic considerations. This is best carried out by an interdisciplinary team so that a viable timber sale which meets all design requirements can be implemented. The same is true for such projects as non-structural range and wildlife improvements (e.g., treating sage brush or willow), structural range improvements (e.g., spring developments), and/or recreation developments (e.g., construction of trailheads or trails). In all of these instances, though the projects are identified in the FORPLAN solution for a geographic area, there is a necessity for field inspection and professional judgment on the exact location and methods to be used. Guidance for this level of project design is provided by management requirements (standards) included in the Plan for each practice, as well as the description and design criteria included for each ecosystem state (Shoshone Management Goal) selected for each area of the Forest. In this way, latitude is provided for use of professional judgment while providing consistency between implementation and all assumptions supporting FORPLAN analysis as well as results of that analysis.

There are at least two other features of this analysis procedure and resulting Forest Plan that appear to simplify implementation. The first is the ability to deal with questions regarding cumulative effects. Each project identified for a geographic area was selected to alter the current state of an area and achieve a specific ecosystem state. Because these states and analysis were designed to take spatial and temporal factors into consideration, it was possible to estimate the overall effects of all projects selected for a specific geographic area within analysis supporting the Forest Plan. In effect, this accomplishes a cumulative effects analysis. Geographic areas included in analysis were large enough (5,000 acres to 40,000 acres) to capture those effects which would be significant for wildlife, visuals, recreation, vegetative diversity, and hydrological considerations. Therefore, as long as projects are designed to meet management requirements included within the Forest Plan (including achievement of specific ecosystem states), then the cumulative effects analysis supporting the EIS for the Forest Plan can be used through "tiering" of environmental documents to support project environmental analyses.

A second feature that aids implementation is the ability to use FORPLAN reports to provide information for budget proposals and disaggregation of budgets (and targets) to Districts. Boundaries for geographic areas within FORPLAN did not cross District boundaries. Using an option from V2 FORPLAN referred to as flat files, it is possible to use FORPLAN to create District by District information systems listing the amount and cost of each practice, as well as estimates of production levels for each good or service to be implemented during the first decade (or any other decade for that matter). Database management/report writer software on the Forest can then be used to display this information and these displays can be used as a basis for developing "project files" that include costs by management code for each project to be implemented. Such project files can then be used to build budget proposals as well as disaggregate budgets and targets to Districts.

Conclusion

The focus of timber planning analysis, until recently, was to estimate acres to be treated and/or volumes that could be produced in order to move toward achievement of a "normal" forest condition in a systematic and regular way (e.g., nondeclining flow of timber production). Linear programming methods for solution of this problem were developed using the same simplifying assumptions underlying tabular methods. These linear programming methods provided analysis tools far more flexible than tabular methods and capable of addressing "optimal" solutions. Because "problem" formulation and simplifying assumptions built into these models did not change from those assumed for tabular methods, solutions generated using these models could not be anything more than solutions generated using tabular methods; that is an estimate of an allowable sale quantity based on biological/silvicultural considerations that may be feasible in terms of on-the-ground considerations.

This type of solution is appropriate for the problem as defined, particularly if one accepts as appropriate a mixed scanning approach to planning and implementation. That is, that solutions so generated are estimates of volume and that such estimates can be revised during implementation. But, solutions are not normally viewed as estimates, rather they are often translated into "hard targets" and used as measures of performance for field managers. This can result in a conflict between these solutions generated using simplifying assumptions and what appears viable on the ground.

Further complicating this situation is the fact that the "problem" to be resolved in timber analysis has changed. Timber analysis (or planning) is now part of Forest Planning with attendant expectations of feasibility of solutions; estimation of all relevant costs, benefits, and multiple-use production effects of applying silvicultural treatments; and close ties to actual implementation of projects.

Three methods for addressing this new problem were discussed. The first of the three "approaches" above really never addresses solution of this new problem and can be dismissed. The second of these methods can be apparently classified as a full mixed scanning approach. In this approach, solutions from FORPLAN are combined with decisions on management emphasis for specific areas based on non-FORPLAN analysis at the Forest level during Forest Plan development. Once a Forest Plan is finalized, these two are combined in a series of post-plan analyses commonly referred to as area analysis. Focus of this analysis is to identify integrated sets of projects that will achieve the overall management emphasis of a subforest area while producing volumes of timber which approximate the allowable sale quantity. Because of the time involved in these post analyses, discrepancies between that called for in the Plan and that actually produced may not appear until near the regularly scheduled time for Forest Plan revisions. Taken as a single, though staged, analysis procedure, this approach does appear to adequately address solution of the new problem facing timber analysis/planning. Full application of this approach, however, may require significant time (a decade) and questions can be raised regarding the adequacy of analysis supporting the published Plan.

The third approach attempts to capture all analyses included within the second approach, but accomplishes this prior to publishing the Forest Plan. This can be viewed as an incremental step in applying a mixed scanning approach because it includes all/most analyses involved in the second approach. A more appropriate classification of this approach, though, is an applied "systems approach" to planning and management. By altering analysis assumptions, as well as problem formulation, it appears possible to implement this approach using V2 FORPLAN. This approach appears to completely resolve the new problem facing timber analysis. Costs and time involved are significantly less than approach 2. And the ability to move directly into implementation in a traceable and supportable manner are significantly improved. Further, other benefits of this approach may include an enhanced ability to involve the public, tiering of environmental analyses (e.g., cumulative effects), and providing an information base to support budget proposals as well as disaggregation of budgets.

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The Next Generation of Planning Analysis in the Forest Service

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Abstract.--The Forest Service has received a substantial amount of criticism on the analysis procedures used during the first round of planning. As a consequence there has been a search for simpler tools for use in analysis during plan implementation. Simultaneously a handful of forests are building new FORPLAN models as part of their forest planning analysis. These facts lead to the need for the Agency to have a plan for improving the analysis done by forests. An overall framework is proposed in this paper for accommodating the short term needs of the Agency while allowing the flexibility to adapt to new planning analysis tools as they become available.

The title of this paper may lead you to believe that there will be an enlightened discussion of some new high tech analysis procedure for the Forest Service. Actually a different tack is taken. I intend to examine some immediate needs which face the Forest Service and, in so doing, build a case which argues the next generation of analysis is upon us now. The format of the paper will be to discuss some problems facing us, examine criteria for resolving the problems, propose a framework for solving the short term problems, and set the stage for future analysis in the Forest Service. The basic premise behind this paper is while some parts of the organization are examining the big picture, work continues. If we do not improve our analysis procedures now, we will be vulnerable to appeal and litigation over the same issues upon which we have already been taken to task.

There are three related facts which present problems to the agency. First, we have received substantial criticism both from inside and outside the agency on the analysis procedures and tools which were used during the first round of forest planning. This is, in no small part, due to the fact that in the rush to complete forest plans the analysis which was done was not understood, interpreted, or refined to the extent possible. Consequently, the analysis has not been used as it might have been; and some have questioned its usefulness. The second fact is in part a response to these concerns. As part of plan implementation, there is a search for simpler more user friendly analysis tools. Finally, we have several forests building new FORPLAN (Johnson et al. 1986) models to respond to concerns over earlier work, to address new information or issues, or as part of the next round of planning. It is imperative that the lessons learned from past analysis be made available to those undertaking the next generation of analysis.

It should be noted that this paper does not address the quality of information used in analysis. Even though this is an extremely important issue, it goes beyond the scope of this paper. The framework presented below emphasizes the significance of quality information on the decision process.

In the next section, I will explain in greater detail why these facts are problematic and develop some criteria which will help to resolve the problems. This paper assumes the reader has some familiarity with the Forest Service planning process and FORPLAN. If not, consult FORPLAN: An Evaluation of a Forest Planning Tool (Hoekstra et al. 1986) and the National Forest Management Act (NFMA) Regulations (36 CFR part 219). It is important to give credit to the many people who have been working to integrate and simplify the information flows and analysis in forestry. This paper is a compendium of ideas from many sources interpreted in the Forest Service context and in the current hardware/software milieu. A partial list of the sources of many of these ideas follows: Northern Arizona University's Terrestrial Ecosystem Analysis and Modeling System (Dykstra et al. 1987), Forest Service Region 1 (Merzenich 1986, Tanke 1986, Timko 1986), Region 5 (Barber 1986), Chattahoochee-Oconee N.F. (Hilliard 1986), Integrated Pest Impact Assessment System (IPIAS - White et al. 1988), Kirkman et al. (no date), Nicolet N.F. (Loh 1987), Davis and

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Reisinger (1987), Weisz and Carder (1975) and Long Range Direction for Timber Management Information Systems (Sonnen 1984).

EXPLANATION OF THE PROBLEMS

Criticisms of FORPLAN

Criticisms of forest plan analysis have spanned the spectrum from "too much" to "not enough." The "too much" criticisms generally relate to too big, too complex, too costly, too time consuming, etc. (Bare and Field 1986). On the other hand, some critics say there are not enough choices, not enough alternatives, not enough spatial detail, etc. (These sorts of criticisms are embodied in many appeals.) Forest Service analysts have echoed similar concerns during the development of forest plans. However, there has been no consensus on the appropriate level of detail. Upon closer examination, many of the criticisms from both the technical and non-technical critics stem from poor explanations of the assumptions and decisions embodied in the model. On the results side, failure to explain model interactions and implications account for many of the criticisms.

Beyond concerns about how analysis was done, some critics are asking why the Agency chose FORPLAN as its primary analysis tool (Bare and Field 1986, Johnson 1986). Many alternatives have been suggested ranging from no computer analysis to even more complex systems embodying risk and uncertainty. However, none of the alternatives have been given the "acid test" in the forest planning context.

Certainly there is an element of truth in some of the criticisms leveled at forest plan analysis. However, some of the criticisms call into question the planning process as outlined in the regulations. Such questions will be examined when the regulations are reviewed next year. In the meantime it is necessary to assume the regulations will remain about the same and to proceed.

Simple Implementation Approach

Frustrations with FORPLAN analysis within the Agency have been a major force influencing the attitudes toward analysis in plan implementation. In a sense, there has been a backlash against seemingly complex analyses. On the other hand, the job of plan implementation is, in many cases, as complex as the job in forest planning, if not more complex. The process used to implement the plans is the basic National Environmental Policy Act (NEPA) process which makes it similar to the forest planning process. However, in the forest planning process, spatial considerations were at a larger and simpler scale. When it comes to laying out projects on the ground which comply with the plan standards and guidelines and do not foreclose future options or our ability to meet targets, the problem becomes fairly complex. In the face of these difficulties and the close scrutiny given many of our projects, many implementors are choosing simpler tools (in some cases no tools are used). Some of these simpler tools are surprising in their capabilities. However, their use leads to several concerns. First, although integration can occur at several points in the process, there is less certainty that it will occur if not included in the analysis step. Moreover, it becomes more difficult to estimate and document all of the environmental consequences of proposed actions. Approaching implementation without integrated analysis fosters a return to functionalism. In many instances the discipline with the tools is in the driver's seat with other specialists relegated to a reactionary role.

Beyond this is the problem of painting oneself into a corner. While this is not a universal problem, some forests will have difficulty finding a way to lay projects on the ground to meet the outputs specified in the forest plan. It can be demonstrated that a casual approach in the short run will lead to an inability to obtain necessary outputs within the plan standards and guidelines in subsequent time periods. Some tools are available to help avoid this problem. Of these tools, some have been shown to provide more economically attractive solutions (Jones et al. 1986). This fact is particularly important in view of the below cost sale issue facing many forests.

It should be noted while many of the tools on micro and mini computers are excellent, their alleged simplicity is open to question. They may be easy to run once the data set is built, but collecting the necessary information and putting it into the model is not always a trivial task. Moreover, many of the tools, while seemingly simple for small prototype problems, quickly become an input nightmare when attempting to do real problems, e.g., spreadsheets. Finally, many of these tools lack error checking which may lead to erroneous results.

When thinking about the role of analysis in the Forest Service, it is important to examine the audience which will be using the tools. During the first round of planning, we had a substantial number of trained analysts. Many of them have moved outside the Agency or into mainstream jobs within the Agency. During plan implementation, the analysis job is being undertaken by other resource specialists. Another trend is for employees on districts to do more analysis. Hence, the market place for analysis tools has changed. Users are less sophisticated and, after having experienced "user friendly" systems, will not tolerate old software technology.

The Next Generation of Analysis

One would think, following all of the work done to produce the 15-year plans, there would be a lull in forest planning analysis. This would provide an opportunity to evaluate what was done before and how things can be improved. Obviously, we will attempt to do this; but, as frequently occurs, there is an immediate need. The Tongass National Forest is revising their 1979 plan, and they are building a new model. The Bridger-

Teton and the Arapaho-Roosevelt National Forests are also building new models to respond to criticisms of their earlier analysis. Also, a number of forests are either in the process or considering building new models to update their analysis and to make a better tie to plan implementation. What this means to me is that the next generation of analysis has begun. To avoid making the same mistakes that were made in the first round of planning, we need to help forests improve their analysis. The remainder of the paper will lay out criteria for improving analysis in the Forest Service and provide a recommended framework for analysis in the Agency.

PROBLEM RESOLUTION CRITERIA

Solving these problems necessitates the development of a set of criteria which will determine when and if the problem is resolved. Admittedly the criteria presented below are general, but they can be refined as work progresses. Before launching into the criteria, however, it is necessary to build a case for the use of FORPLAN in the next generation of planning analysis. Once this is taken care of the important issues related to solving the defined problems can be addressed.

The Case for Using FORPLAN in Forest Planning

In NFMA Congress essentially adopted a rational comprehensive approach to planning (Teeguarden 1987). Teeguarden (1987) further states:

> "NFMA and the implementing regulations require some form of mathematical modeling of the land management system to insure program feasibility, incorporate technical relationships, reflect resource availability, insure decisions are consistent with policy objectives and constraints, and for conducting tradeoff analysis."

Later in the same paper he notes:

> "Also, the model must have a capability for handling analyzing timber management programs including temporal harvest scheduling, identification of suitable timber lands, rotation policy and selection of appropriate silvicultural systems."

Teeguarden concludes FORPLAN is very strong in meeting 19 forest level analysis requirements that he infers from the NFMA regulations.

Rodger Sedjo and John Sessions summarized the symposium, FORPLAN: An Evaluation of a Forest Planning Tool. Sedjo (1987) concluded:

> "While FORPLAN has potential to be very useful as a decision making tool in public forest management, this potential has not yet been realized because of the model's tendency to be overly large and comprehensive. To be useful the model needs to be used for more limited purposes in more simple and smaller forms. In addition, the FORPLAN tool should be supplemented with a variety of more specific analytical tools that have tactical and on-the-ground applications."

Sessions (1987), in contrast, made these closing remarks:

> "...I must conclude there is general agreement that FORPLAN has made a significant contribution to forest planning. The economists, the ecologists, and the managers here have largely been satisfied by the ability of FORPLAN to adequately represent their concerns and address issues at the forest level. Over the last several days I have played the devil's advocate to draw out criticisms of FORPLAN and the criticism is surprisingly mild. Perhaps we are exhausted after 10 years of planning?"

My conclusion, based on these reviews and my own experience, is that FORPLAN is a useful and legitimate tool for continued use in Forest Planning. Needless to say there is still room for improvement and this will be addressed in the second half of this paper.

The Case for Using FORPLAN in Plan Implementation

Careful examination of plan implementation reveals that the process is virtually the same as forest planning. The major difference is in the scale of the analysis and the detail of the results. Analysis for plan implementation should result in enough detailed information to allow people at the district level to carry out projects as well as disclose site specific environmental consequences. For example, in FORPLAN, you may substitute project areas (e.g., cutting units) for analysis areas to achieve more spatial detail. Model formulation changes can also be made to assist with plan implementation. Adding adjacency constraints and transportation network formulations helps perform project analyses on subunits of a forest ranging from 10,000-50,000 acres in size. Therefore, with minor modifications of information used and model formulations, implementation analysis can be conducted using FORPLAN (see example 3 for more details).

It is also important to note that much of the information used by national systems is implementation and monitoring oriented, for example, the Resources Planning Act (RPA), Land Management Planning (LMP), and Program Development and Budgeting (PD&B), Joint Data Base (DB), Timber Sale Program Information Reporting System (TSPIRS), Sale Tracking and Reporting System (STARS), etc. The general framework proposed below is applicable at all levels of planning.

Assumptions

In addition to the presumption that FORPLAN is a good tool upon which to improve, the following assumptions are also made in developing problem resolution criteria.

1. The Forest Service will continue to do long range forest planning of some sort.
2. Long range forest planning will incorporate an analytic approach.
3. Planning analysis requirements will not lessen but may even increase.
4. Limited funding and personnel ceilings will make formally trained analysts scarce.
5. There will be a dramatic increase in hardware, software, and communications capability in the next 5 years (Chi 1985).
6. Information flows are in response to decisions being made and their attendant documentation.

Criteria for Analysis and Analysis Tools

Given the problems facing the Agency, analysis performed in the future will have to meet certain criteria to be successful. This is by no means an exhaustive list but includes some criteria considered critical.

Analysis Criteria

1. A clear statement of the role of analysis in forest planning.
2. Simplified acquisition of production and economic information.
3. Solutions that have more spatial content.
4. Models designed to address critical issues.
5. Management realization that size and complexity of models is an investment decision.
6. Help for analysts and managers understanding model results.

All but the first are self-evident. During the first round of planning, the role of analysis was not crystal clear. Many hoped that FORPLAN would provide not only long range analysis, but project level analysis as well. In other words, planners and managers hoped FORPLAN results could be taken to a ranger and the ranger would know what, where and when things needed to be done on the ground. There was also an objective to reduce the amount of NEPA documentation required when implementing projects. Although a couple of forests succeeded in this goal, most were unable to get the kind of spatial detail in the model they desired. The limitations were twofold: limits on model size and the cost of solving large models.

In the meantime, as forests began implementing their plans, they discovered that the projected outputs were estimates and had to be treated as such. The thrust of plan implementation has evolved to managing acres within the approved standards and guidelines. However, it would be naive to think output estimates can be ignored altogether. Some constituents place a lot of importance on these figures. We also learned that the NEPA requirements for project implementation would be overwhelming if done at the forest level. Add to this fact the analysis results contained only part of the information necessary to select a preferred alternative, and it becomes obvious FORPLAN did not provide all of the answers.

Together, these trends have led to the following role for analysis in the Forest Service. Analysis is used to aid decision making. It provides information to decision makers, so they have a better understanding of the implications of their decisions with the goal being improved management. Furthermore, in the forest plan context, the analysis results can be viewed as a zoning of the forest with the schedule of activities and outputs representing anticipated outcomes of such a zoning under an assumed level of management. Finally, the role of forest plan analysis is a strategic analysis. We acknowledge additional environmental analysis will have to be done before site specific projects can be undertaken (in this context analysis does not necessarily imply using a computer). Given the role and the analysis criteria, there are criteria analysis tools must meet:

Criteria for Analysis Tools

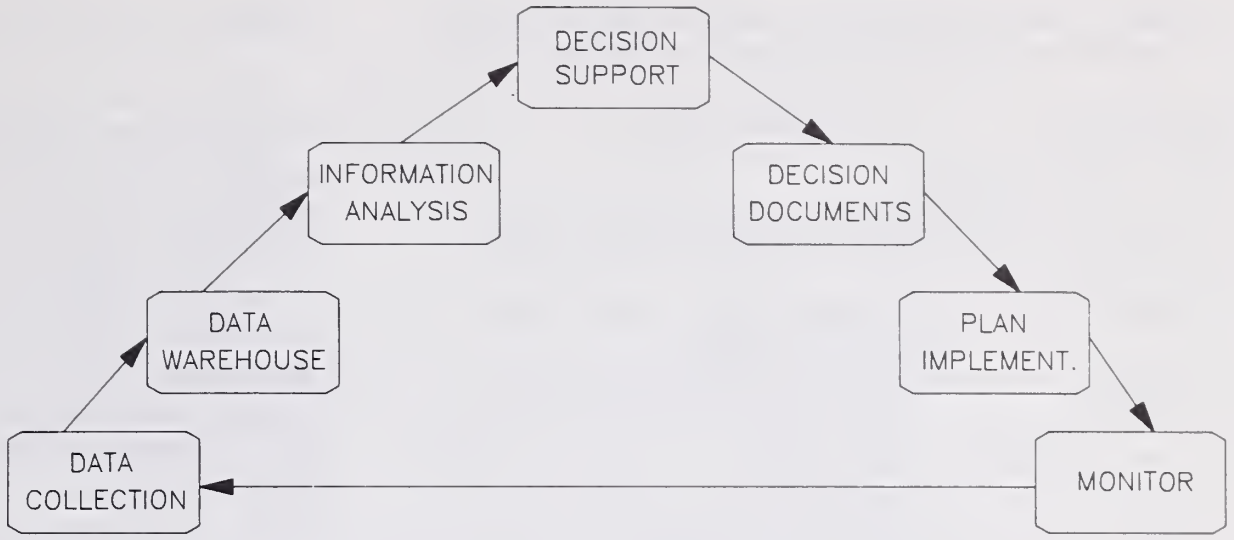
1. Provide assistance in choosing the best tool to address problems.
2. Provide assistance in understanding model results.
3. Provide assistance in creation of analysis data sets.
4. Provide assistance in understanding linkages that need to be made in analysis data sets to achieve desired results.
5. Simplify acquiring production and economic information.
6. Simplify the relation of analysis results to other agency data bases and reports.

A FRAMEWORK FOR ANALYSIS IN THE FOREST SERVICE

Simplifying Analysis in the Forest Service

In this section of the paper, I will outline a framework for analysis in the Forest Service. It is designed to address the stated problems within the criteria which have been developed. The framework accommodates the short term needs of the Agency while allowing the flexibility to adapt to new planning analysis

tools as they become available. Briefly, the framework is based on a foundation of organizational information management. A broad view is taken of the planning problem rather than focussing merely on decision support systems. Three major areas for improvement are identified: (1) improving information flows, (2) simplifying use of tools, and (3) helping people use tools more effectively.



EXAMPLES OF TOOLS USED TO PROCESS, ANALYZE AND STORE INFORMATION IN FOREST SERVICE PLANNING.

INVENTORY STND EXAM FINSYS	PERM PLOT TMIS IRIS	GIS GRO & YLD IRIS	FORPLAN IMPLAN SIMULATION	FOREST PLAN EIS EA	GIS FORPLAN SIMULATION	TRACS TSPIRS JOINT DB

Figure 1.--Information flows in Forest Service planning.

Improving Information Flows

A major time-consuming job during the first round of planning was the collection, organization, and analysis of resource data prior to being entered into FORPLAN. Not a lot of attention was paid to this problem at the national level, because each region was organizing things differently, and we were busy refining FORPLAN. Now, however, the climate has changed. We have a standard computer system, work is underway on a corporate information structure, and there are many standard data bases and reports in place. The corporate information structure is intended to provide a data and information base which is easily understood and shared by all users. It is predicated on a corporate information base, data standards, common data definitions, and a technology to support information flow (Rains 1987). Such a climate has a major impact on how we should proceed with analysis in the Forest Service. If a corporate system is in place, then the analysis tools can capitalize on the standardization; and some real efficiencies can take place in information management. Such an approach will greatly reduce the unending translation of information which has taken place in forest planning.

Therefore, the time is right for examining planning information flows with the goal of integrating them into the corporate information structure. Once this is accomplished, tools can capitalize on common data structures and definitions. This approach has a big payoff in terms of simplifying the collection of information for analysis. Furthermore, it is a step toward standardizing information definitions so analysis results aggregated at higher levels of the organization can be used effectively. A simple view of the information flows in the planning process is shown in figure 1. An important point is that a system such as FORPLAN resides in only one box of this diagram. There is a large complex of information needed to support the analysis. In turn, the analysis results are used in many ways within the Agency (fig. 1, table 1). Both points relate to how we can improve forest plan analysis. Clearly, the quality of analysis depends on the information feeding into it. Simplifying the movement of information into analysis tools will dramatically reduce the time it takes to build forest planning models. For example, being able to create analysis areas automatically from a Geographic Information System (GIS) would save a substantial amount of time (Rains 1987). The quality and usefulness of information reported to our constituents and to other levels of the organization also depends on the ease and consistency of reporting. Finally, our ability to learn and improve information and management depends on closing the feedback loop through the monitoring process. Thus, one major component of simplifying and improving planning analysis is to simplify and improve information flows.

Simplifying Use of Tools

The second major area of improvement is to simplify the use of each part of the overall planning system. For example, within the Decision Support Box (fig. 1), FORPLAN can be improved by making it easier to use. An obvious improvement is to have input screens for parts of the data input. This can be done either through screen generating software or by using a data base management system front end (Bevers and Kent 1988). However, as described above, major parts of the input such as the analysis areas and yield tables actually come from other data bases. Here, improvements can be made in supplying yield information in FORPLAN format as output from simulation models (see the examples in later sections of the paper).

A not so obvious improvement, but perhaps the improvement with the biggest payoff in terms of quality of analysis,

Table 1.--Forest Service tools used to process, analyze and store: Information in Forest Service planning.

System Name (or Acronym)	Description
1. Inventory	Forest level timber inventory data.
2. Stand Exam	Stand level timber inventory data-usually for projects.
3. FINSYS	Software to summarize and report inventory data.
4. Permanent Plot	Data base for storing permanent plot inventory data.
5. TMIS	Timber Management Information Systems (data base).
6. GIS	Geographic Information System.
7. Growth and Yield	Any one of several timber growth and yield simulators, e.g., PROGNOSIS.
8. FORPLAN	Forest Planning Model (linear programming).
9. IMPLAN	Economic Impact Assessment Model (input-output).
10. TRACS	Timber Activity Control System (data base).
11. Simulation	E.G. DYNAST, Mark Twain N.F. Simulator, Project Area Scheduling System (PASS).
12. TSPIRS	Timber Sale Program Information Reporting System.
13. Joint Data Base	RPA, LMP and PD&B Joint Data Base.

would be an advisor to help users formulate and construct a FORPLAN data set. This can be done through a combination of an expert system and data set templates.

The experience we have gained from past analyses indicates there are certain capabilities most everyone needs for forest planning analysis. Examples of these capabilities can be included in data set templates. Likewise, for implementation analysis, model templates can be constructed which provide the basis for forest analysts to construct customized forest models.

Another improvement with a large payoff, especially considering our new user community, is an advisor to help explain results. Many have suggested the results of planning analysis are difficult to understand. Yet, a competent analyst can explain and understand the results. If we can capture the expertise of competent analysts, other users will have assistance in understanding and interpreting results.

There are certain key indicators which can be used to test for reasonableness and to explain changes, for example, timber inventory at the beginning and ending of the planning horizon, long term sustained yield capacity, and acres allocated to key management emphases.

Helping People Use Tools More Effectively

Simplification is not the only issue however. Analysis must be tailored to the issues facing the forest. I have seen improvement along these lines in recent modeling efforts. However, analysts are still grappling with spatial resolution versus modeling size problems. Some suggestions have been made on how to reduce model size while placing the emphasis on the short term (Barber 1986, Bowes and Krutilla 1987). One approach ignores the problem of scheduling management prescriptions by geographic area, while the other puts the burden of developing a coordinated schedule on the user (Johnson et al. 1986). Neither approach is the ideal. What we would really like is the ability to develop schedules, at least for the short term, by geographic area. If we expect the user to develop coordinated schedules, we find it is labor intensive and subject to criticism for not being comprehensive. Instead, I am suggesting unique analysis areas be developed by geographic area for critical areas.

The approach outlined capitalizes on the ability of computers to deal with combinatorial problems. Software can be developed to facilitate the input burden which might otherwise be imposed on the user. The generalized Model 2 structure of Version 2 FORPLAN can then be used to collapse the spatial detail after the second period. Analysis areas that are harvested are sent to collapsed regeneration classes as usual. The difference is existing stands not harvested within the first two periods would also be collapsed spatially to reduce model size.

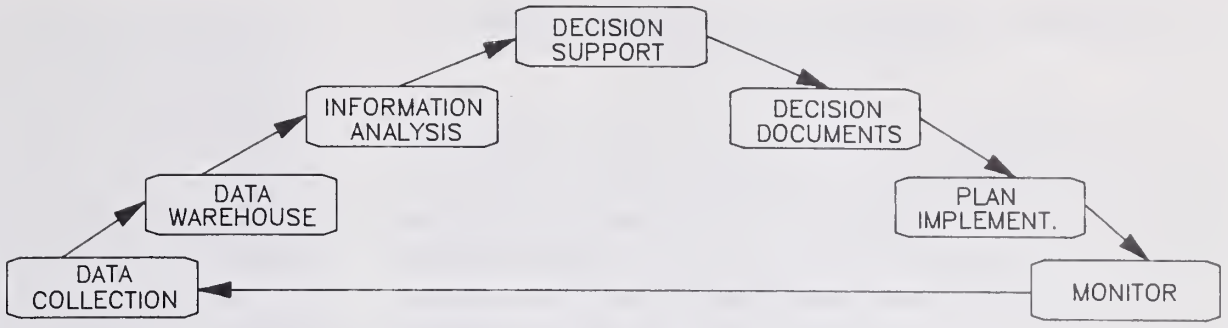
Although resulting models could be approximately as large as current models, the results would provide valuable spatial detail in the schedule. This simplifies the step of checking implementability, makes results much more meaningful to district rangers, and saves time in the overall planning process. Moreover, it allows geographic specific constraints (e.g., habitat dispersion) to be applied to models. Similarly, geographic specific economic information, such as haul costs, can be more readily incorporated into the model. Examples of this type of model formulation must be made available to users so they can start well up on the learning curve of providing useful analysis.

Anticipating the Future

Object Oriented Design

In addition to simplifying model construction using existing tools, we must prepare for changes in tools as improvements are made. This fact argues for a modular approach allowing the modules to be replaced without disrupting the entire information flow. Object oriented programming embodies concepts such as these and may be a useful paradigm for the system development (Coulson et al. 1987, Gomsi and Desanti 1987). An example of the advantages of this approach is in the development of a user interface for the analysis module. The

interface can be common for several different analysis tools, (e.g., simulation and optimization). An expert advisor would lead the analyst through a sequence of questions to pick the best tool for the current problem. Once the tool is selected, a tool specific advisor helps the user construct the actual model. As new analysis tools are developed, they can be added as an option or substituted for obsolete tools. Such an approach has a high payoff, because the majority of the information used in analysis, no matter what tool is used, is the same (e.g., economics, activities, outputs, production relations, management requirements, etc.).



EXAMPLE 1. FLOW OF INFORMATION INTO THE DECISION SUPPORT SYSTEM.

INVENTORY STND EXAM	INDIVIDUAL TREE DATA	PROGNOSIS	FORPLAN YIELD TABLES	FOREST PLAN		

EXAMPLE 2. AGGREGATING INFORMATION FOR HIGHER ORGANIZATIONAL LEVELS.

				FOREST PLAN	IMPLEMENT. ANALYSIS	JOINT DB

EXAMPLE 3. DISAGGREGATING FOREST PLANNING SOLUTIONS FOR IMPLEMENTATION.

INVENTORY STND EXAM	INDIVIDUAL TREE DATA	PROGNOSIS	FORPLAN YIELD TBLS ADJACENCY RELATIONS	EA	TIMBER SALES	STARS

Figure 2.--Examples of improving the planning and implementation process.

The Hardware Dilemma

Another major tenet of the framework being proposed here is modules should be designed, to the extent possible, to be hardware independent. The important decision is to choose hardware which has the capability to perform the needed function efficiently. While this sounds trite, many analysts have been interested in a micro version of FORPLAN (Johnson 1986). Presently, the micro version will not generally handle real problems, even at the implementation scale, because of limits in Linear Programming (LP) algorithms. This is not to imply a matrix might not be generated on the micro and transferred to the mainframe, solved, and a compact report returned to a micro or Data General (DG). Rather, I am implying in the short term, micro computers are not the answer for useful FORPLAN analysis. Given the shortage of processing power on the Agency DG systems, we will opt for a dual strategy which will allow a common front end to run on either the DG or a micro. Eventually, we anticipate that micro computers will be able to solve our problems and this approach incorporates that eventuality.

EXAMPLES OF IMPROVING THE PLANNING AND IMPLEMENTATION PROCESS

To clarify the general concepts described above, several specific examples illustrating improved information linkages with decision support tools will be presented. The illustrations demonstrate how timber information flows from raw stand information to information used in plan implementation and to information used at the National level.

Example 1. Flow of Information into the Decision Support System

Most forests must take a careful look at their timber program in forest planning, both to satisfy the intent of NFMA and to address public issues. Typically this is accomplished by identifying lands potentially suitable for timber management and for management of other resources using timber harvest. Next, prescriptions are developed which define different sets of management objectives for the lands. In turn, activities for achieving the objectives are identified and the outputs and environmental effects of the activities are estimated. If, for example, timber management practices are used, one of the outputs will be timber volume. The question is, given a set of management practices, what volume will be produced? (Realize here that I am narrowing the focus to a single resource for the purposes of illustration.)

PROGNOSIS (Wykoff et al. 1982) is a stand simulation model of the single tree type. It provides yield projections with or without management for existing or regenerated stands. In the first round of planning, the Interdisciplinary (ID) Team generally defined the prescriptions and then a silviculturist would run PROGNOSIS to develop yield projections within the assumptions of the prescriptions. The results of the PROGNOSIS runs had to be translated into the proper format to be entered as yield tables in FORPLAN. Some Forests probably did this manually, while others used computer programs. Although there are many ways to create FORPLAN models and .timber yield tables, there is enough commonality in the way most forests have approached the problem to warrant development of generalized software to facilitate the translation (fig. 2).

Example 2. Aggregating Information for Higher Organizational Levels.

A second example is the PD&B, LMP, RPA Joint Data Base. A project is underway in our Washington Office to create a common data base for these three planning functions. Congress is interested in how budgets relate to implementing forest plans. In addition, they are interested in how forest plans relate to RPA. The goal is to use common data definitions to achieve consistency among the three planning functions, to reduce the number of information requests to the field, to improve integration and information sharing among the three staffs, and to satisfy all information requirements. Presently all Forest Service Regions are meeting these information requirements in different ways. The plan is to develop a Structured Query Language (SQL) data base with a common set of information. Much of the information included has its origin in forest plans. The information required by the planning function, in fact, comes directly from forest plans. RPA information generally requires some amplification from the preferred forest plan alternative, while PD&B information generally requires some refinement. The refinement normally takes place during implementation analysis and when developing program budgets. In all cases, the base information is derived from the plan. Thus, there is an opportunity to provide tools for moving, in an automated fashion, information from FORPLAN solutions to the joint data base. Again, this would be a labor-saving enhancement and would lead to more consistency in the results (fig. 2).

The National Computer Center at Fort Collins (NCC-FC) is planning to build a system to facilitate information sharing and handling among data bases between the DG and the mainframe (USDA 1988). Features of the system are:

1. Menu architecture for applications development.
2. Forms design facility.
3. ANSI Structured Query Language (SQL).
4. Integrated data dictionary.
5. Report writer.
6. Data base administration utilities.
7. Security facilities.

Such features could help move plan information from the mainframe to the Joint Data Base on the DG. In a similar fashion such a system may facilitate plan implementation where much of the information is on the mainframe.

Example 3. Disaggregating Forest Planning Solutions for Plan Implementation

Heretofore forests have faced a significant challenge once they selected their preferred forest plan alternative. The challenge was to disaggregate the FORPLAN solution to the ground such that they knew where the scheduled activities should occur (Keller 1986). Many strategies have been adopted for solving this problem from simple to sophisticated. The approach described here has several features to help address this problem. First, the proposed mathematical formulation (see Helping People Use Tools More Effectively) will allow a more site specific solution. The intent is to obtain activity schedules by user defined geographic areas. Beyond this is the notion of adapting the forest-wide FORPLAN data set to site specific models to perform what is known as area analysis for project analysis and scheduling (Ryberg and Gilbert 1986). Fairly simple modifications to the forest-wide data set results in an area analysis template which can then be adapted to each area where optimization analysis is needed. All that must be added are the project areas (e.g., cutting units), proposed roads, adjacency relationships (if appropriate, Meneghin and Jones 1988), output targets (e.g., desired volume for the area), and standards and guidelines (often in the form of constraints). In addition, some yield estimates may be refined either by including site specific yield data or by refining the PROGNOSIS runs to more accurately represent the site (fig. 2).

Consider the case where during project analysis a timber sale is identified as necessary for implementing the forest plan. The timber sale is entered into the Sale Tracking and Reporting System (STARS). The NEPA process is used to provide public notice and comment. When the decision is made an appropriate NEPA document is produced [Categorical Exclusion (CE), Environmental Assessment (EA) or Environmental Impact Statement (EIS)]. STARS continues to be used to track the sale until a contract is awarded. There is an opportunity to automate the link between the project analysis and the sale tracking system. The benefit would be a reduced workload for district resource managers.

But, suppose a sophisticated tool such as FORPLAN is not needed. This is the problem an advisor is designed to solve. It helps the user examine the problem at hand to determine what level of analysis is necessary and appropriate. Various levels of tools should be available from simple economic calculation programs to sophisticated simulation models. The user selects from an array of tools the one that best analyzes the current problem.

SUMMARY AND CONCLUSIONS

Significant opportunities exist for simplifying and improving analysis in the Forest Service. Foremost may be an improved understanding of the role of analysis in forest planning. Next, the realization that the tools we have available meet our analysis needs. However, improvements need to be made along three fronts: (1) improving the flow of information from information sources to analysis tools, (2) simplifying the creation and use of analysis models, and (3) making the analysis results more useful. By accomplishing these tasks within the criteria outlined above, we will make large strides toward solving the

problems discussed at the outset. Even though the analysis will probably always be criticized for political reasons, at least now the results will be more useful, more understandable, and more easily accomplished. A simple approach to analysis will continue to be our goal. However, when problems require sophisticated analysis for solution, we will help guide analysts to use the proper tools. Furthermore, if the whole analysis process is made easier and faster, reluctance to its use will diminish. Software and hardware technology hold promise for making these improvements now. It is imperative the Forest Service undertake these enhancements so we can improve the next generation of analysis based on the lessons learned from our past experiences.

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Design Considerations for LP-Based Forest Planning Systems: Perspectives from FORPLAN

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Abstract.--Over the past decade FORPLAN has evolved into a large and complex linear program modeling system for decision support in forest planning. Although FORPLAN employs a highly sophisticated data deck design and reporting system for card image batch processing and high speed printing, recent strides in user interfaces on desktop and office machines present new opportunities for future planning systems. Design considerations for this new processing environment, including possibilities such as an interactive desktop data set manager, a mainframe batch submittal system, dynamic core allocation, heap storage, and flexible array packing, are discussed.

Since the late 1970s, the USDA Forest Service has been heavily involved with the development of multiple-use land management plans. This activity has been conducted in compliance with the National Forest Management Act of 1976 and its attendant regulations (USDA Forest Service 1982). Early on in this activity, the role of a linear programming (LP) based system, FORPLAN, as principal analysis tool was established.[2]

Experience with this first version of FORPLAN led to the development of a second version in 1982 (Mitchell and Kent 1987). Because the relevant background information has been covered elsewhere, we will not provide a detailed discussion in this paper. An excellent account of the evolution of both versions can be found in Iverson and Alston (1986). For additional information on the evolution of FORPLAN, as well as descriptions of each of the versions, refer to Johnson (1986) for an overview of FORPLAN Version 1 and Johnson et al. (1986) for an overview of FORPLAN Version 2. Descriptions of the technical criteria used in the development of FORPLAN be found in Jones (1987) for Version 1 and in Weisz (1987) for Version 2. Details on how FORPLAN was used for national forest planning applications can be found in the two overview documents cited above, as well as in Mitchell and Kent (1987).

Much of the early development of both versions was done by Dr. K. N. Johnson, now at Oregon State University. However, as Mitchell and Kent (1987) point out, after this initial work, additional development, user support, training, and system maintenance responsibilities were taken over by Forest Service personnel (specifically by the Land Management Planning Systems Section in Fort Collins, Colo.). During the 8 years the Systems Section has functioned in this role, considerable experience in various facets of the FORPLAN system has been gained. One of these facets related to questions of overall design for an LP-based planning system such as FORPLAN. The purpose of this paper is to provide a discussion of some of the potentially more significant ideas for system redesign. Simply put, given the lessons learned from this experience, "where might we go from here?"

Background and Organization

Much of the FORPLAN systems work done by the Forest Service has been guided by two principal objectives (Gast 1986):

1. Simplify and enhance the system, and
2. Reduce run costs.

It seems logical to assume that these objectives will continue to be of concern. Although they can be and often are conflicting,

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[2]USDA Forest Service. 1979. Letter from Douglas R. Leitz, Associate Chief, to Regional Foresters and NFS Directors. 1920: Development and use of forest planning model. December 3.

it is reasonable to specify a goal that the redesign ideas discussed below be directed towards providing efficient modeling capabilities to the national forest planners.

As a framework for our discussion, we make the following assumptions about future national forest planning activities:

1. LP will continue to be the central analysis tool used.
2. Models will continue to be very large and complex. Criticism about size, cost, and complexity (Bare and Field 1987) seem to be offset by criticism calling for more spatial detail and site-specific analysis (Shugart and Gilbert 1987).
3. The recent achievement of significant advances in the whole arena of computer science will continue.

Chi (1987) gives an excellent description of implications of computer related advances. He identifies seven significant trends, two of which, and especially the second, have particular significance to much of what we discuss below. The first of these trends Chi refers to as, "sustained exponential price-performance increases." The major significance of this trend for our purposes stems from the fact that both new and powerful hardware environments (e.g., distributed systems, intelligent work stations, and micro computers) and new and different software applications are now possible.

The second trend relates to what Chi calls a change in objective function. Specifically, he states:

> "...the objective for the first 20 to 30 years in computing was to maximize systems performance. In contrast, the objective function today is to maximize user performance."

On the hardware side, the new environments mentioned above made computing and computers available to many, including those with no prior experience.[3] Demand for and interest in using computers increased with this availability and a primary focus became making things easy for the neophyte user. Many of these efforts involved the development of what has become known as "user friendly" software. A real problem is the fact that, as Chi (1987) points out, it takes a tremendous amount of computer and manpower resources to develop and operate effective user friendly systems.

We will use Chi's trends to refine our efficiency goal by considering both system and user efficiencies in developing redesign ideas. From this point on, we will assume that FORPLAN Version 2 (henceforth FORPLAN) is the system of interest. FORPLAN, like many other systems, evolved in what might be termed a traditional mainframe environment where the focus was on system efficiencies rather than user efficiencies. Because of this, it is reasonable to expect that significant gains in user efficiency can be made with FORPLAN in an interactive distributed workstation environment. It is important to recognize that, as Chi (1987) points out, there will be a significant price to be paid in terms of increased system size--a price that will manifest itself in terms of both computer and maintenance resource requirements. This suggests the existence of a tradeoff between system and user efficiencies.

An example of the implications of this tradeoff can be found in the FORPLAN evolution that has already taken place. FORPLAN Version 1 had an input data organization and input procedure that was very difficult for users to understand (Weisz 1987). In an effort to resolve this, a different set of data input and organization conventions known as DE FORPLAN was developed. While this approach alleviated some of the earlier problems, it left users with data sets containing up to 2.5 million card images. The user was thus overwhelmed with the care and feeding of unmanageably large data files. This problem was resolved with redesign efforts that went into FORPLAN Version 2; however, the resultant changes in system size were significant. The DE FORPLAN code required about 65,000 words of main memory to execute while the enhanced code requires almost the system limit (under UNISYS Corp. Operating System Exec level 39) of 262,000 words. The number of lines of executable source code requiring maintenance increased from around 5,000 to 36,000.

Three additional factors that will influence FORPLAN users and their environment merit mentioning here. The first is that our assumption about the continued development of large LP models has important implications for the tradeoff between system and user efficiencies. It will not be feasible for several years to solve these large models on workstation equipment. Thus, model solution will still require centralized processing and support. The significance of this is that in order to enhance user efficiency, FORPLAN jobs will likely have to be partitioned among two or more systems in the future. The second factor is that the situation with FORPLAN differs in one detail from the first trend described by Chi (1987). This difference is that, unlike overall industry costs, mainframe processing costs on the USDA UNISYS computers have not decreased significantly over time. We surmise that this is because they primarily support costs. The third factor that will play a role in system enhancement, and this is true for any system, is the software development lag. Software development projects, such as new operating systems, etc., typically run 100% over budget and a year behind schedule (Carroll 1988). This becomes critical when enhancements to a system like FORPLAN are dependent on capabilities that must come from software developed by others. As an example, to function effectively on a micro computer, FORPLAN requires an operating system that can address more than 640 Kbytes of main memory (the limit for MS-DOS). An operating system with this capability has been promised for 2 to 3 years and is just now becoming a reality.

An important implication of the above seemingly disjoint collection of observations is that any redesign efforts for FORPLAN cannot afford to focus solely on user efficiency. System or code related efficiencies must also be considered and the tradeoff between the two mentioned above is very real. The organization of the remainder of this paper attempts to reflect

[3]Our interpretation of this cause and effect relation differs somewhat from Chi's in that the suggests that the focus on the user is the driving force behind the change from centralized to decentralized computing.

this. The next section will consider redesign ideas that enhance user efficiencies. The following section will serve the same purpose for system efficiencies and the final section will look into the question of the development of linkages between FORPLAN and other systems.

Redesign Considerations for Increased User Efficiency

In this section of the paper we focus on three opportunities for redesign efforts leading to increased use efficiencies. The first relates to user interfaces with FORPLAN input data sets, the second to user interfaces with FORPLAN solution reports, and the third to FORPLAN run preparation and submittal.

As has been pointed out, data is currently input in a card image format. In addition, the organization of this data, while improved over that of Version 1 and DE FORPLAN, is still difficult for users to understand. As a result, data preparation and development of an understanding of the linkages between different data types are difficult tasks for many users. Currently, data sets are developed with some type of text editor, with only written documentation, format instructions, and previously developed data sets available for guidance. The only way to verify correct data set development is by processing the data against the matrix generator's data interpretation and error checking routines in a batch run. As if these problems were not enough, the information provided by the matrix generator comes in the form of a large (often more than 1,000 pages) hard to read batch printout.

Major (and interrelated) problems faced by a FORPLAN user in this environment include the following:

1. It is difficult to develop and debug data sets, especially if any of the more refined FORPLAN system modeling capabilities are incorporated.

2. The task of data verification is difficult and often not completely carried out. This is caused in part by the fact that the user has access to many optional features and a complete bullet proofing in the matrix generator against all possible errors is not feasible.

3. There is a real danger that users become so involved with the data error elimination game that they never develop an adequate understanding of how to use and/or revise their data in order to adequately model and analyze their problems.

4. A very steep learning curve must be faced by anyone new to using FORPLAN even if he or she has an existing data set and FORPLAN analysis results to work with.

Two approaches can be taken to partially resolve some of these problems by moving away, where possible, from a batch processing environment and all that it implies. Complete resolution, however, is not likely because of the complexity of the forest planning application. The first approach involves development of software that permits data set development in a user friendly interactive environment. Key improvements of such a system would include data entry screens, on-line help capability, and interactive data set debugging facilities. These components would be designed so that the user could build a data set in a modular fashion using interactive help and error checking features. FORPLAN data sets are frequently modified and this activity would be facilitated by this type of interactive environment. Because of the complexity of FORPLAN data sets, this system would not be easy to develop and, in addition, modification of both the matrix generator and the report writer would be necessary to incorporate the necessary data set modularity.

An alternative approach would involve the change in thinking implied by changing the term data set to data base. The key element of this approach would be the development of an interactive data set manager. This tool would be used to develop, debug, and/or modify a FORPLAN data base. In addition, this approach would provide the user with query capability. As an example, a user might want a list of all prescription decision variables on an area of the forest that link to a particular constraint. Most likely, this data base manager would be developed as a relational data base (Codd 1970), although the hypertext approach (Goodman 1987) expert systems (Partridge 1986) and object oriented programming (Gilbert this proceedings) also offer some promise. While these approaches differ in detail, they all offer the user the ability to organize and view data in forms that make the data items, their organization, and linkages more intuitive. The payoff is an increased understanding of what needs to go into a FORPLAN data set in order to do effective analysis.

The next area that has potential for increased user efficiencies is that of FORPLAN solution reports. As is the case with the matrix generator and data development, solution reporting is done for the most part in a batch processing environment, often resulting in large printouts. The current report writer uses the same input data as does the matrix generator and offers reasonable flexibility in terms of user report selection. However, as Bevers (1986) points out:

> "A shift in computer programming emphasis from specialized, mainframe-based reporting systems to more generic, transportable programs which primarily provide linkages to other software is an attractive change whose time has come for the Forest Service. Today's commercially available software packages for charting, graphing, and other reporting are both powerful and easy to use."

Users often need either additional analysis of solution results for such things as plan implementation or more refined reports than FORPLAN can produce. Until recently their only alternative was to develop their own utilities to process the input data and solution reports. In 1986 a flat file reporting capability (Bevers 1986) was added to the report writer. This enabled the user to generate solution reports in a form that could be

transferred to a Data General minicomputer and processed against Data General "Present" report writing software.

The flat file capability offers a partial solution to the report problems mentioned previously. However, a more general and potentially useful alternative exists. This would be to generate solution information in relational data base form and then use a structured query language processor to develop the desired reports or additional analyses. Note that this solution is similar to one posed above for input data problems.

The final area for potential user efficiency increases is that of FORPLAN run submission. As alternatives to the mainframe (such as mini- and micro-computers) become more available, and as user friendly systems such as those discussed above are developed, more and more FORPLAN jobs will be run on multiple systems. As an example, a particular job might consist of data construction, matrix generation, LP model solution, and then solution reporting, with the first and last steps being done on a mini- or micro-computer and the LP generation and solution being done on a mainframe. When a job is partitioned across more than one system, a considerable amount of file transportation and job control language interfacing (usually with more than one operating system being involved) is necessary. To make all of this easy, a job submittal software system that would insulate the user from dealing with all of the details would be most desirable. The user would interface interactively with this software on the hardware system of choice (likely Data General mini-computers in the Forest Service). He or she would only need to specify the type of job, the information specific to this job (i.e., the location of input data files, etc.), and possibly the nature of the job partitioning. The batch runstreams necessary to actually execute the job and transfer files between systems would be built and executed by the submittal system.

Processing Efficiency Considerations

As was pointed out earlier, FORPLAN has grown immensely in recent years as the Systems Section has tried to accommodate requests for new modeling features and tried to make the system easier to use. FORPLAN has become too large and too expensive to ignore processing efficiencies, and the user-oriented redesign proposals outlined in the preceding section could further exacerbate this problem if not carefully implemented. At the same time, opportunities for improving the current processing capabilities should be explored as well. Consequently, efficient approaches to job partitioning and memory management warrant examination.

The typically large sizes of national forest planning models suggest a logical approach to job partitioning. As Kent et al. (1987) point out, these models commonly range in matrix size from 100,000 to 3,000,000 non-zero LP coefficients. Even if micro-based workstation CPUs, IO transfer rates, and mass storage devices could satisfactorily support the number crunching and file addressing demands of such models, the need currently to upload the problem to a mainframe computer for LP solution makes it impractical to generate the matrix locally at a distributed processing site. The prospects for telecommunicating hundreds of thousands of LP matrix records per model are simply not good. While it is desirable to move the jobs of building, debugging, and storing the model data, as well as interpreting solution results, onto local workstation equipment, both matrix generation and LP solution will continue to require mainframe resources in the near future.

Although FORPLAN jobs could be partitioned in this fashion by just building new workstation tools without modifying the mainframe system significantly, there are some advantages to redesigning the mainframe code. Such tasks as card image transfer and processing could be reduced, and redundant tasks, such as data error checking and matrix printing could be eliminated. However, the big payoff to revising the mainframe code would be in enhanced memory management.

The data set management and job submittal system software proposed in this paper could handle not only the principal model data, but by storing appropriate counters and array pointers, could manage memory allocation parameters for the receiving mainframe system. Ideally, the submittal system could send the mainframe host a FORPLAN job with a mixture of "core images" for common array and pointer values, card images for analysis area lists, directly entered prescriptions, and yield tables, and a set of model parameters for memory management. As an example, a principal model parameter to pass would be the total amount of computer memory required to process a particular model. This would provide a fast-loading system that could streamline processing through dynamic core allocation, heap storage techniques, flexible packing schemes, and common-banked instructions.

Dynamic core allocation would give FORPLAN the ability to have each model occupy exactly the amount of core memory required for that model. Currently, all FORPLAN models, however small, occupy 256 Kwords of main memory, or about 1 megabyte. Through dynamic core allocation, system impacts and user charges for smaller models could be greatly reduced.

In order to support dynamic core allocation, both heap storage techniques and flexible packing schemes would be desirable. As FORPLAN has grown and matured, hard-coded array dimensions (and model section size limits) such as 5 objective functions and 100 activities and outputs have been replaced throughout the system with adjustable size parameters. The parameters allow the variation of size limits and memory allocation much more easily, but only by completely recompiling and collecting the entire source code. Once the parameters are set, that space is always allocated in memory whether needed by a particular model or not. Heap storage techniques employ the use of an increased number of pointer variables to allow maximum freedom within core array space. Thus, if no temporal flow constraints are used in a model, as an example, the pointer would be left null and that array space would not be allocated, leaving more memory available for other model input sections or free core.

As long as memory addressing continues to be more limiting than processor speeds, maximum use of dynamic core allocation will require flexible packing schemes. FORPLAN programmers have increasingly had to employ specialized data packing to keep within existing hardware and operating system limits. However, these procedures for storing multiple values within single addressable storage words of memory currently work from known imposed FORPLAN limits. Since FORPLAN programmers know, for example, that there are only eight thematic identifier levels allowed and that each level may use no more than 100 identifiers then each set of eight identifiers is packed into two 32-bit computer words of storage using seven bits for each level identifier sequential number. If we are to truly remove programming-imposed limits and make full use of dynamic core allocation, these packing schemes must be made both flexible and general. This change would also open the door to increased model flexibility since users would no longer be constrained by programming limits such as eight thematic identifiers levels, but rather by total memory and processing limitations.

Before moving on to common-banked instructions, three final points about heap storage and flexible packing must be made. The first point is that both of these techniques are far more easily and efficiently done in the "C" programming language than in FORTRAN, which is currently used. The second point is that as memory becomes cheaper and more easily addressed (Chi 1987), data packing may become unnecessary and even inefficient. Finally, the ability to gain this degree of memory flexibility is critical to ideas expressed in the next section of this paper.

Impacts on memory resources, and the associated run costs, could also be reduced by moving to common-banked instruction sets. Often in the past, four FORPLAN models have been processing in core concurrently at the USDA National Computer Center in Fort Collins. For each of the models, separate complete instruction banks along with the necessary data banks have been loaded into core. By moving the FORPLAN instruction set into a single shared resident common bank accessible to all users, total memory requirements could be reduced by about 1 megabyte. Each FORPLAN job would be smaller and more easily accommodated in core during peak processing times.

Linkages to Other Systems

In the previous two sections of this paper, we have emphasized the significant time and resource investments needed to learn FORPLAN, to build and debug data sets, to solve the resultant LP models, and to generate and interpret solution reports. Acquisition of the information needed to build or modify a FORPLAN input data set also requires a considerable investment in time and resources.

Mitchell and Kent (1987) discuss the types of information that can be utilized in a FORPLAN input data set. Briefly, the types of information most likely relevant to this discussion are information on land strata and the vegetation occupying them, information on prescriptions, information on costs and returns associated with management practices, and yield information pertaining to production levels of various goods and services. This section of the paper will briefly address ideas that have the potential to increase user efficiencies in the input data acquisition and updating arena.

First we consider data pertaining to the land base and existing vegetation. The basic strata in a FORPLAN model are called analysis areas and are typically defined by combinations of attributes such as current vegetation, slope, soil type, administrative boundaries, etc. There will usually be from 200 to 700 analysis areas defined for a given National Forest and these will be the result of aggregating several thousand more precisely defined land parcels called capability areas.

Up to now, the formidable tasks of defining, locating, and measuring the size of capability areas, of aggregating these into analysis areas, and of incorporating this information in FORPLAN input data have been done largely by hand. In addition, the disaggregation of FORPLAN solution results back to these strata has also been done manually for the most part. A contributing factor to the size of these tasks is that there are often too few direct relationships between FORPLAN layers (identifier or thematic levels) and the layers used to define capability areas.

With the Forest Service moving (although slowly) into GIS technology, there is real potential for increased user efficiencies in this area. First, this will permit automating much of the job of land and vegetative base inventory information management. This is important for many reasons, not the least of which is the ability to quickly update these inventories as a result of plan implementation activities, catastrophes, new information or any other factor that changes this data. Secondly, this will facilitate the development of automated linkages between GIS data bases and FORPLAN analysis area data. As an example, one real plus to the increased user flexibility described earlier in this paper is that with some thoughtful design, the number of FORPLAN layers (currently at most eight are available) could be made more flexible as well. This could provide the opportunity for automated linkages between FORPLAN and GIS layers (or map overlays). The need for thoughtful design of FORPLAN output (be it either on a screen or in printout form) to support this flexibility cannot be overemphasized.

We close this section of the paper with a general observation about the other types of information mentioned at the beginning of this section. The key point here relates to the fact that much of the economic and yield information is generated by various software systems such as yield simulators. There are opportunities to develop linkages between these simulators and FORPLAN data sets. This linkage software could be used to automate development and updating of the relevant sections of FORPLAN input data.

Conclusions

From what has been discussed in this paper, it is obvious that changes in computer technology along the lines of those described by Chi (1987) have the potential to significantly alter and improve the interfaces between users and a large system such as FORPLAN. These changes have great potential for improving the users' lot in life. However, it is important to recognize that while it is relatively easy to outline them conceptually in a paper such as this, actual development of systems necessary to implement the changes will be something else again. The key question is, do the ends justify all the additional work? In our opinion, they do.

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Experiences with FORPLAN--A Distillation to Two Proceedings from a Research Prospective

Brian M. Kent, John G. Hof, and Linda A. Joyce[1]

Abstract.--In 1986, the USDA Forest Service sponsored two meetings focusing on the forest planning tool FORPLAN. The first meeting was an internal workshop addressing the topic of lessons learned during the first round of national forest planning. The second meeting was a symposium involving participants from both in and outside the Agency and its purpose was to provide an evaluation of FORPLAN. This paper contains a review of the proceedings published for the meetings. The focus of this review is on potential research topics that would address problems relating to future planning efforts.

In 1986, the USDA Forest Service sponsored two meetings pertaining to the Forest Planning system FORPLAN. The first was a national workshop that explored the lessons learned in the agency through the use of FORPLAN. The participants at this workshop were almost exclusively Forest Service personnel. The second was a symposium whose theme was an evaluation of FORPLAN. Unlike the workshop, there were numerous non-agency experts and members of interest groups in attendance, in addition to agency personnel. These external experts played the lead role in the evaluation, with background and supporting information being provided by agency experts.

Proceedings of both of these meetings have been published (Bailey 1986, Hoekstra et al. 1987). Both proceedings contain useful information and recommendations on a number of subjects pertaining to National Forest planning, FORPLAN, and the agency's planning process. The purpose of this paper is to focus on one subject, the ideas, and recommendations pertaining to future research and development activities. We will summarize the relevant information from each meeting and then conclude with some general observations. Since the ideas expressed came from a diverse group of individuals both in and out of the agency, particular attention will be paid to any common "themes" or frequently repeated recommendations.

THE INTERNAL WORKSHOP

As is pointed out in the preface (Bailey 1986) the main purpose of the workshop was:

> "...to serve as a forum to share experiences with FORPLAN, to better understand how best to capitalize on past successes and avoid pitfalls as we head into plan implementation, and prepare for the next round of planning."

As this statement implies, while the main focus of this workshop was not research, the potential for the discussion of numerous research related topics was high.

A review of the 33 papers and the recommendations of the three working groups bears this out. We group the problems that were identified into four categories as follows:

1. the agency's planning process, the role of Forest Planning within that process, and the role of analysis in planning;
2. the need to be able to conduct additional analysis, such as sensitivity analyses;
3. the need to improve existing data and acquire new data; and
4. miscellaneous topics such as plan monitoring.

Clearly, these categories are interrelated in terms of their implications for research and we shall point out some of these relationships. What follows is not an enumeration of all references to all problems, but a sampling of references to the most important problems identified by workshop participants.

PLANNING PROCESS/ANALYSIS

This is probably the most important area of concern and to one degree or another, all the other problem areas will be

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affected by the way in which these issues are resolved. Throughout the proceedings, there is evidence of widespread concern about the roles of both forest planning and analysis. Line officers (Ehlers 1986, Voytas 1986) expressed a concern that FORPLAN is a tool to aid in making decisions rather than the decisionmaker--a point that they feel is often misunderstood. Iverson (1986) points out that both the limits of modeling and the role of models, providing insights instead of answers, are not always as well understood as they should be. Wong (1986) raises the question of how much detail is really required to do forest level planning.

Some of this confusion may stem from the lack of personnel who are well trained in planning and analysis, which is an institutional problem rather than a research question. On the other hand, at least some of it undoubtedly arises from a lack of precise definitions pertaining to the roles of the different levels of planning and the types of analysis that needs to be conducted for each. The first two recommendations from Working Group #3 make this point:

> "The Agency must better define the role of forest planning in the context of the overall planning job for the agency. Once Item 1 is accomplished, the role of FORPLAN and analysis can be more clearly defined and perhaps simplified."

Both of these points suggest research priorities. As an example, there exists a rich body of literature on planning theory that has never been considered by agency planners and analysts. Workshop participants offer several suggestions for research efforts pertaining to the role of analysis and modeling approaches.

Several authors (Barber 1986, Greer 1986, Voytas 1986) stress the need for simpler, more understandable models and approaches to analysis. Troyer (1986) observes that models which are expensive and difficult to use are not what the agency needs and that any system must help accomplish the agency's mission. Of course, the point is also made repeatedly in the two meetings that the development of a multiple-use land management plan for a National Forest is not a trivial exercise and may therefore require the use of sophisticated systems to carry out complex analyses.

Iverson (1986) points out the limitations of mathematical programming as is currently used in FORPLAN, while Stage et al. (1986) suggests that the use of simulation models either with or instead of optimization models be investigated. They also stress the need to improve our ability to incorporate uncertainty in forest planning analysis. Wilson (1986) points out that FORPLAN can be used effectively both as a simulation and an optimization model. Finally, Connelly (1986) and Mitchell (1986) recommend that a multi-stage approach to forest planning be investigated. All of these ideas have potential, but for them to be investigated effectively, the overall agency planning process, the role of forest planning within that process, and finally, the role of analysis must all be more clearly defined and understood.

NEEDS FOR ADDITIONAL ANALYSIS

Within this problem area, three general categories of analysis are identified: spatial, sensitivity, and budget level analysis. Spatial analysis is perceived as a problem because it is difficult to represent in a linear programming (LP) model (Connelly 1986). It is, however, an important consideration from the viewpoint of many resource specialists. However, should it be addressed as part of forest planning and/or as a part of plan implementation (Keller 1986)?

The need for sensitivity analysis arises both from the poor quality of some of the data in FORPLAN models and from the problem of uncertainty (Greer 1986, Wilson 1986). Unlike spatial analysis, well known procedures are available for conducting a sensitivity analysis of an LP model. Such an analysis is, however, expensive and time consuming when conducted on large LP models such as those that are often generated with FORPLAN. Greer (1986) suggests that a formal assessment of agency needs for sensitivity analysis be conducted, that smaller/simpler models be used where possible to facilitate sensitivity analysis, and that additional user friendly operations research tools be developed to facilitate sensitivity analysis.

The importance of analyzing the impacts of different budget levels on plan implementation is pointed out by Leonard (1986), while Hof et al. (1986) feel that this type of analysis is critical for the effective use of forest planning information in national planning.

REPRESENTATION OF OTHER RESOURCES/DATA QUALITY

This problem area relates to two general concerns, the incorporation of resources other than timber into forest planning analyses, and the improvement of the quality of the data used in these analyses. Leonard (1986) points out that better ways must be found to incorporate non-priced resources and minerals in FORPLAN models and the planning process. Connelly (1986) and Lee (1986) comment on the difficulties of representing wildlife and fish resources in FORPLAN.

Troyer (1986) observes that the accuracy of forest planning data bases must be improved. This point is also the basis of one of the recommendations of Working Group #2, especially in terms of needs for the next round of planning. Concern was expressed pertaining to the difficulty of estimating benefits (Wilson 1986). He also points out the need to design future resource inventories with forest planning data needs in mind.

Standardization of FORPLAN models and data is suggested by Weisz (1986). Working Group #1 recommends that data standards be developed with particular attention being paid to the need to be able to aggregate information upward within the agency. Hof et al. (1986) point out the need for data and analysis consistency between forests in order to facilitate national planning. Standardization may also offer advantages in terms of simplifying analysis. To some degree, data and analysis stan-

dardization is an institutional issue, but care must be taken to insure that mindless standardization, at the expense of innovation and creativity, does not occur. Research into how this might be accomplished would be important if standardization is going to be given serious consideration.

Miscellaneous Topics

A few other problem areas that have research implications are suggested by workshop participants. Keller (1986) suggests an approach to plan monitoring that involves the development of a metric to measure the convergence of forest conditions to the desired or steady state condition. Working Group #2 recommended the development of a flexible system for project and plan implementation analysis. Hilliard (1986) suggests that such a system should be developed with the recognition that this analysis will be conducted at the Ranger District Level. Finally, Hagestedt (1986) comments on the importance of retaining records of the experiences and lessons learned by agency personnel during the first round of planning and suggests the use of artificial intelligence systems to help accomplish this.

THE FORPLAN EVALUATION SYMPOSIUM

We now turn our attention to a review of the symposium on the evaluation of FORPLAN. The symposium was organized into three sessions, the first addressing the development and implementation of FORPLAN by the Forest Service, the second recounting experiences in the implementation of FORPLAN by non-agency users, and the third containing the evaluation of FORPLAN including implications for management and research. We will discuss relevant recommendations from each of these sessions, with our primary focus being on the third session.

SESSION 1--FORPLAN DEVELOPMENT AND IMPLEMENTATION

There are three papers in this session which discuss topics that relate to research. The first of these, Teeguarden (1987), provides background information on the adoption of a "rational comprehensive" planning philosophy (Lindbloom 1959) in the National Forest Management Act (NFMA) and its associated regulations (USDA Forest Service 1982). This philosophy has had a significant effect both on how FORPLAN has been used and on the recommendations for research made in the other papers presented at the symposium.

Teeguarden also develops a list of 24 analysis and documentation requirements that result from the NFMA regulations. Nineteen of these are forest level requirements, eight of which FORPLAN can potentially satisfy. These relate to planning alternative analysis, vegetative manipulation, and land allocation. The other 11, relating to nontimber resources, can be partially met with FORPLAN but other models or analytical processes are also needed. The five remaining requirements relate to concerns that go beyond the forest level. Two of these, species diversity analysis and economic impact analysis, can again be satisfied in part, with FORPLAN. The other three, determination of viable vertebrate population levels, federal/state/private coordination, and cumulative effects analysis, lie clearly beyond FORPLAN's capabilities.

Based on all of this, Teeguarden suggests some research priorities. These include the development of improved methods for modeling demand in forest planning, improved methods for viable population determination, and the development of models and analysis procedures to facilitate cumulative effects analysis and coordination with other governmental agencies and the private sector.

Teeguarden closes with some observations on the question "will comprehensive planning work?" He expresses the concern that if it fails, it will be a major setback for the forestry profession. He also stresses the importance of a comprehensive evaluation of what has been done in the first round of planning.

The second paper (DeAngelis 1987) provides a discussion of the first session papers from the perspective of a quantitative ecologist. He addresses four basic issues pertaining to the adequacy of FORPLAN as a modeling framework. These are:

1. the optimization approach,
2. linearity of models,
3. spatial resolution, and
4. uncertainty.

In terms of optimization modeling, DeAngelis points out the difficulty of representing nonmarket valued commodities and ecological considerations in a model based on a financial criterion of optimality. With regard to linearity, he notes that ecological systems are often highly nonlinear and in fact, under extreme circumstances, may be discontinuous. In such situations mathematical catastrophe theory is suggested as an alternative. The third issue, spatial resolution, is in his opinion, handled to some degree by FORPLAN. However, many important ecological spatial aspects such as landscape heterogeneity are not dealt with adequately. The fourth issue, uncertainty, is difficult to address in FORPLAN models, especially when the size of these models is considered. Sensitivity analysis may partially alleviate this problem, but its usefulness is perceived as limited for large models. He suggests a modification to the FORPLAN approach that permits the selection of suboptimal strategies if they significantly reduce the probability of undesirable outcomes.

The final first session paper discussed is Johnson (1986). While his main focus is on the development of FORPLAN, he does point out a number of problems that could require further investigation. The first problem relates to the question of emphasizing economic efficiency versus estimation of environmental effects. In his opinion, the agency has structured both the

NFMA regulations and its approach to analysis to focus on the former. From an analysis viewpoint, Johnson sees this problem as manifesting itself through the selection of an optimization approach over simulation approaches. The answer to the question of modeling approach is, at least in part, driven by the nature of the planning process (in this case, the NFMA regulations). As was pointed out repeatedly in the internal workshop, both of these questions merit further investigation.

Johnson goes on to point out that the model structures and use of FORPLAN have never been published in the scientific literature. He also expresses concerns both about the survival of integrated planning in an agency organized along functional lines, and about the implications of reduced budgets on plan implementation.

Johnson raises a few additional points. External reviewers of forest plans will be concerned as to whether "efficient" prescriptions are adequately represented in FORPLAN models. Given a definition of "efficient" this area is amenable to research. He notes, as have other authors, the problems of uncertainty and overly complex models. He recognizes that because of the complexity of the planning problems being addressed, it may not be easy to simplify models, but he feels this must be accomplished. Like Teeguarden (1986), he feels that sound cumulative effects analyses must be conducted. Johnson also suggests that the results of analysis and plan implementation could well become important building blocks for the next set of forest plans. This idea (also suggested by West (1986) in the workshop) has intuitive appeal and is another area with research potential.

SESSION 2--EXTERNAL FORPLAN EXPERIENCES

This session contains two papers that address possible research problems. Davis (1987) suggests two relevant research roles for the FORPLAN system. One of these is an investigation of conditions favoring even versus uneven-aged timber management systems. The other relates to the use of FORPLAN to help facilitate coordination of Forest Service planning with that of other agencies and the private sector. Davis also makes the point that FORPLAN could be a very useful tool for conducting policy analysis studies.

Dellert (1987), points out that FORPLAN would be a more attractive system if it could be simplified and easily linked to other planning systems such as a geographic information system. This would form an overall planning system, and such a comprehensive system would undoubtedly be useful to the Forest Service.

SESSION 3--FORPLAN EVALUATION

In this session, FORPLAN was evaluated from three perspectives, economic (Beuter and Iverson 1986), ecological (Shugart and Gilbert 1986), and operations research (Bare and Field 1986). Each of these evaluation papers was accompanied by two discussion papers. We now consider each set of three papers in turn.

The Economic Evaluation

The central theme of Beuter and Iverson (1987) is that a system such as FORPLAN cannot possibly determine a thorough and precise optimal solution to the forest resource allocation problem encountered in Forest Planning. They identify several purposes for such a model that suggest research priorities: a means of focusing the planning process, a means of comparing the long term effects of alternative plans, a means of opening the planning process and revealing the paths by which a solution is obtained, a base of knowledge and a focus for negotiation, a means of improving education and communication between all interested parties, and a means of improving decisionmaking through all of the above.

In evaluating FORPLAN as an economic tool, they identify several characteristics of an "ideal forest planning model" that also suggest research priorities. They suggest that the ideal should: be capable of maximizing net social welfare, consider the long run, distill all that is known about markets and seek an efficient allocation of factors of production to meet demands for goods and services from the forest, and easily make (analyze) tradeoffs between different forest resources (reflecting joint production).

In pulling the above observations together, Beuter and Iverson note the important tradeoff between technical capability of a system such as FORPLAN and complexity that makes understanding difficult. They suggest that developments which improve technical capability without resulting in "total unintelligibility" from some perspectives would be the best developments of all.

Beuter and Iverson also discuss the linkages between FORPLAN applications and: the RPA Program and the budgeting process, forest operations, and the outside world. Regarding the RPA Program and the national budgeting process, they conclude that insufficient linkages exist and that a fundamental inconsistency exists in that the budgeting process is functional (dealing with individual line items) while forest planning is oriented towards a more integrated analysis of jointly produced forest outputs. Regarding forest operations, they conclude that "what appears optimum for the forest may not be optimum for a watershed." They also state that the "link between operational feasibility and forest plans is tenuous..." Perhaps most strongly, they conclude that "It is debatable whether it [FORPLAN] should be used for large-scale, forest-level planning...Version 2 may be best suited to site-specific project analysis..." These observations suggest a many-leveled optimization problem that is interactive from the national level down to the project level, where omission of detail is unacceptable as is lack of central coordination. The implied research and development problems are substantial. Regarding the outside world, they observe that

"there has been little effort to develop national forest plans with sensitivity for the management of surrounding lands..." They cite Johnson and Greber (1986) in Oregon as an example of a more complete view. Again, the research and development implications of such a problem are quite challenging.

In summarizing their economic evaluation of FORPLAN, Beuter and Iverson note that the way such a model is used is possibly more pivotal than the raw capabilities of the model itself. And, they conclude that the role of FORPLAN in the planning process must be clarified. In their final remark, however, they ask, "If not FORPLAN, what?" Perhaps this indicates the first research need in this area--what are (if any) the alternatives to a large scale linear programming analysis of the forest resource allocation problem? Whether the most fruitful direction is further development of linear programming approaches or some fundamentally different approach, Beuter and Iverson provide the pragmatic guidelines outlined above.

Hof (1987) discusses the Beuter and Iverson paper and expands upon it in two areas: further evaluation of linear programming models in forest planning and linkages with higher levels of planning. Hof discusses four shortcomings of these linear programs.

First, he discusses the distinction between an economically defined production function and the activity analysis implied by a linear program. In terms of research needs and priorities, he concludes that a linear program will most closely emulate the ideal production function if essentially all technically feasible options (activities) are accounted for in the model. Thus, methods for developing these options require research and development.

Second, he discusses the importance and the difficulty of accounting for the spatial layout of management options in linear programs. He concludes that this is a most critical and intractable problem facing forest planning analysts.

Third, Hof questions the need for detailed acre-by-acre land allocations as a result of forest planning analyses. This suggests research oriented towards possible analysis techniques that provide decision rules or guidelines (as in some control theory and dynamic programming problem formulations) rather than specific numeric solutions.

Fourth, Hof discusses the problem of discontinuities in forest resource allocation problems and the limitations of linear programs in dealing with such discontinuities. He suggests research into the area of Catastrophe Theory to address these difficult problems. He suggests that many of the limitations of linear programming attributed to ignoring risk and uncertainty may actually be problems of ignoring discontinuities.

In terms of linkages to higher levels of planning, Hof concurs that such a linkage is clearly needed, and discusses options for achieving it technically. The first option is currently being developed (Hof and Baltic 1988, Hof and Pickens 1987), and involves using the FORPLAN solutions as choice variables in higher level planning models. The second option involves an iterative approach along the lines of Kornai and Liptak (1965). Both approaches are in need of further research and development. Hof also concurs with the fundamental difference in the functional perspective of the budgeting process and the integrated perspective of forest planning. Resolution of this difference is indicated to be more institutional than researchable.

Binkley (1987) identifies six "costs" of utilizing FORPLAN in forest planning: "analysis costs" (the direct costs of developing the system and building the individual forest models), "institutional costs" (potentially adverse effects on the agency from some people being excluded from the highly technical planning analysis, personnel changes, etc.), "increased centralization" (the loss of local flexibility from adopting a standardized planning system), "increased ignorance?" (the possible loss of information or understanding resulting from mathematical representations and models), "planning in a vacuum" (the losses from focusing on individual national forests without consideration of adjacent lands), and "implementation" (the difficulties of actually implementing the plans, including the problem of actual budgets not meeting plan budgets).

Binkley also discusses the "benefits" of the FORPLAN system and concludes that FORPLAN is "partially" effective in determining economically efficient solutions. He points out that reconciliation of political discord was an overriding objective of the new planning procedures. He also states that if simulation is the objective, then FORPLAN, as a linear program, may be "a poor analytical approach, and the principal benefit of linear programming--identification of economically efficient plans--is lost."

In terms of research areas to address the points summarized above, Binkley suggests the following:

1. Analysis of the analytical process itself. What were the costs and benefits of the first round of planning? How did actions change in response to land management planning?

2. Institutional factors. How did the Forest Service change in response to FORPLAN? What kinds of information were systematically ignored because of the modeling efforts? How can this information be brought back into the planning process? What are the limits of procedural rationality in national forest planning? How much technical information can be transmitted via the political system?

3. Large-scale modeling systems. Beuter and Iverson usefully distinguish model efficacy from model efficiency, pointing out that the first implementation of any system is not likely to be very efficient. But now it is time to turn to questions of efficiency. Can the recent advances in solution algorithms for linear programs--Karmarkar's algorithm, gradient projection techniques,...--be usefully exploited in the kinds of problems which arise in land management planning? Are there fast heuristics to take advantage of any special model structures typical of FORPLAN problems?

The Ecological Evaluation

The Problem

Shugart and Gilbert (1987) used 10 ecological facets to appraise the utility of FORPLAN in quantifying ecological processes:

1. non-linearities in ecological relationships,
2. variations in ecological time scales,
3. multiple resource interactions,
4. spatial dimension,
5. variation and error in model coefficients,
6. uncertainty in ecological processes,
7. succession and mortality,
8. dynamic versus static representations of ecological processes,
9. vegetative structure,
10. delineation of land units for analysis.

While Shugart and Gilbert (1987) describe the difficulty that one has in using FORPLAN to quantify these ecological facets, the end result is that analysts found ways to quantify these facets using FORPLAN. The problem was not all facets could be addressed at one time or in one model.

For every facet, Shugart and Gilbert (1987) give an example on how it was handled or how it could possibly be handled within FORPLAN. While the details vary for each particular facet, the approaches could be generally described as discretizing the ecological process and associating the ecological process with a fixed size of land. For example, mobile animal species are transformed into "fixed" resources by enlarging the land unit analyzed in FORPLAN or by linking the animal response with a zone (combination of land units).

Issues Related to Ecology

The struggles in trying to incorporate ecological processes into FORPLAN brought up issues related to the objectives of the FORPLAN model. In every attempt to quantify ecological processes in FORPLAN, model size, or duration of model run (and consequently model interpretation) becomes the real problem. As a result of this need to restrict model size, the "dilemma is deciding how much detail should be carried in the forest planning analysis tool and how much should be handled in separate steps" (Shugart and Gilbert 1987). Shugart and Gilbert (1987) emphasize that "some of the advantages such as reduced FORPLAN model complexity are achieved at the expense of increased analysis before FORPLAN."

Resolving this dilemma requires a definitive answer to the question "What is the objective of the FORPLAN modeling analysis?" Must all resources must be in a *single* decision analysis tool? Shugart and Gilbert (1987) admit that one might argue that the Forest Service should not be trying to do such comprehensive planning involving multiple stands and multiple ecosystems forest-wide, but the NFMA requires a *single plan*. Joyce (1987) suggests that the NFMA requires a single plan, not necessarily a single planning analysis tool, to accomplish comprehensive planning forest-wide. Clearly a closer examination of the modeling objectives is required.

Research Direction

If, as Shugart and Gilbert suggest, "the objective (of the modeling analysis) is to provide information which allows the exploration of resource production potentials using ecologically sound management," then their proposed modeling framework (fig. 1) increases the number and type of analytical tools that could provide information on multiple resource manage-

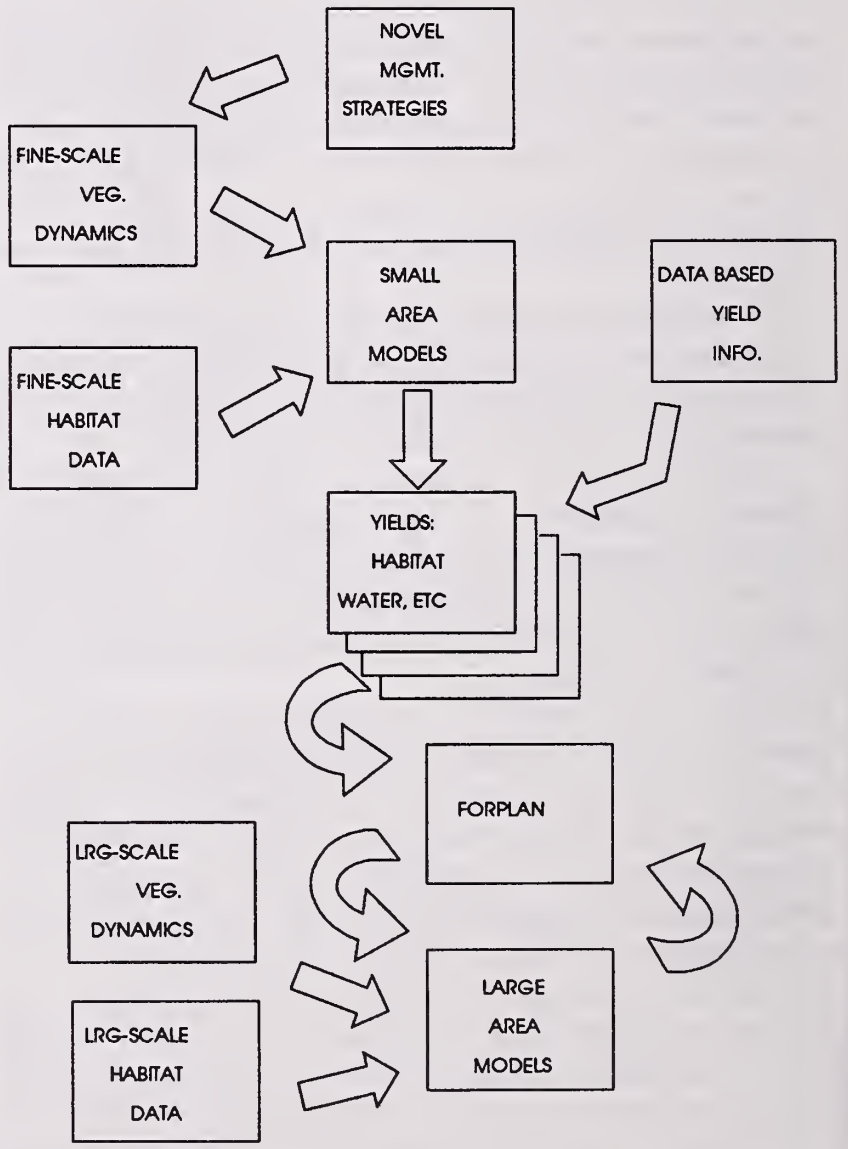


Figure 1.--Example information flows for large- and small-scale simulation as posr- and preprocessors to FORPLAN. Large-scale models also could be used as preprocessors, if appropriate.

ment. This approach as well as that of Joyce (1987) and Milne (1987) recognizes that: (1) resource production analyses need to be quantitatively linked in the planning process but not necessarily in one model, (2) resource interactions occur within different spatial scales, (3) resource interactions occur within different time scales, and (4) there is a need to incorporate the information between spatial and temporal scales in planning.

Shugart and Gilbert point out that "ecological sciences do not have a tradition of using linear programming to any great degree when compared with the well-developed traditions of statistical applications and differential equation models." Thus, the ecological sciences had little to offer in terms of guidance to analysts looking to capture ecological processes using the linear programming modeling approach. Shugart and Gilbert's proposed modeling framework (fig. 1) combines simulation approaches commonly used in ecological sciences with LP models to utilize the appropriate strengths at appropriate places in the exploration of resource production potentials. This proposed approach builds on ideas such as the featured-species plan (Zeedyck and Hazel 1974) and the area-diversity plan (Evans 1974), but adds the concept that changes in the landscape are important to consider in evaluating management activities. Milne (1987) stresses this later point further and describes a number of modeling approaches that might be used to quantify the landscape dynamics under different management strategies.

The FORPLAN model in this hierarchy becomes a land allocation and activity scheduling model where the inputs have been derived from the smaller scale models and the outputs have been examined in the larger scale models. Shugart and Gilbert (1987) stress that the advantages of reduced FORPLAN models are that they are simpler, less expensive to solve, and solutions are easier to check for reasonableness and to disaggregate to the ground. But, they suggest that "perhaps the biggest payoff, is the enhanced ability to comprehend and explain the solutions to management and the public." While FORPLAN has been reduced in this hierarchy, the number of pre- and post-models has expanded, and Shugart and Gilbert conclude that "it is also necessary for ecologists and scientists working with resource managers to explain the significant production functions necessary to make management decisions."

This last point is the most critical in terms of quantifying ecological processes and represents the greatest challenge to ecologists working in this area of research. Is it possible to standardize these production functions? Shugart and Gilbert proposed the key elements that need to be considered in developing an ecosystem/landscape management plan for regional species diversity. While developed for animal species, this approach could be expanded to other resources as well. The key elements are:

1. The ability to associate individual resource output with the features that make up a landscape.
2. The ability to predict the changes in the character of the landscape.
3. The ability to quantify the way species will respond to a dynamically changing landscape. This understanding should be both species-centered (how the dynamics of the ecosystem might effect a particular species of interest) and ecosystem-centered (how the success or failure of a given species might effect other components of the ecosystem).

These concerns can be used to define the research needed to further ecological modeling in forest planning.

1. Can individual resource outputs be quantitatively associated with features that make up the landscape, features that can be manipulated to manage the individual resource output? If yes, then both model building and management may be possible; if no, then perhaps basic research is needed to determine what ecological processes are involved.
2. Can changes in the landscape be predicted? Numerous techniques have been developed to predict changes in the landscape. Milne (1987) described a number of new techniques such as Bayesian models to determine the most likely wildlife habitat within the landscape. The problem here seems to be reliable data and an understanding of the differences across ecosystems.
3. And finally, is the scale of the land unit appropriate for analysis in the FORPLAN model? Shugart and Gilbert (1987) suggest that if the species habitat relations are the same scale as in the simulation model, then the dynamic changes of population as a function of change landscape can be simulated. This would be possible over the observed range for the species and landscape interactions. Thus, for previously observed management manipulations, the response of the species to the landscape could be quantified and used to address management needs.

What Shugart and Gilbert (1987) proposed is in many ways a more formally stated structure of what has/is going on in forest planning analyses. This structure does require additional models which would require additional modeling expertise and data. And while it looks complicated, it is no more complicated than many of the existing modeling structures associated with FORPLAN (Stage et al. 1986). One does have to ask the question as to whether the production information is available. For some resource analysts, not only is the answer to that question no, but also, they feel that we are misleading ourselves to think that the response of ecological systems can be quantified for all possible disturbances. Here again, the objectives of the planning process and the role that quantitative models play in that process need to be defined. Shugart and Gilbert present a framework in which the same model structure is used to examine ecosystem behavior under all possible disturbances. For analysts such as Walters (1986), the appropriate direction for resource management models is an adaptive learning ap-

proach in which an attempt is made to incorporate the dynamics of uncertainty in resource outputs, rather than attempting to describe the average behavior of the production system. This approach addresses two major problem areas, data quality and uncertainty, and merits further study as forest and rangelands become more intensively used and managed.

The Operations Research Evaluation

Bare and Field (1986) begin by determining what an operations research (OR) perspective is. They note that it is a systems approach to problem solving and decisionmaking and that OR practitioners will tend to attack normative or descriptive problems of the widest conceivable scope (Pollack 1986). The OR practitioners presume that a "rational-comprehensive" approach (Lindbloom 1959) will lead to an acceptable solution to any given problem. Bare and Field suggest that the last few years of forest planning raise doubts about the validity of this last assumption.

Bare and Field then turn their attention to an evaluation of the FORPLAN system itself. They begin by examining the mathematical basis of FORPLAN, including its inherent assumptions and their implications for decisionmaking. They also discuss possible alternatives to FORPLAN and recommend an approach to dealing with the next round of planning.

Bare and Field discuss five assumptions/limitations of LP: linearity, additivity, divisibility, certainty, and single criterion of optimality. They point out that linearity itself can be overcome with careful model formulation. Additivity and divisibility, however, are more difficult to deal with. Additivity implies that there can be no interactions between decision variables. Spatial concerns are a good example of how this assumption breaks down in a forest planning application. The divisibility assumption relates to the continuous nature of the decision variables. Unfortunately, most forest planning problems are mixed integer problems where some decision variables are continuous while others can assume only integer values. Examples of the latter type of decision variable include numbers of campgrounds, animals, etc., and timing choices for aggregate emphasis or coordinated allocation choices. Bare and Field suggest that careful formulation and solution interpretation may at least partially resolve these problems. The spatial problem has been identified earlier in this paper as a major research concern. The solution of large-scale mixed integer programming problems is also a significant difficulty, because no solution algorithm equivalent to the simplex method is available. While research into this type of problem lies outside the normal scope of forestry research, the advantages of development of improved methods for solution of such problems cannot be overestimated if the agency is to continue utilizing this modeling approach. Unfortunately, there seem to be minimal prospects for significant developments in this area with the possible exception of improved computing power using existing solution techniques.

The problems arising from the deterministic nature of LP models have been pointed out earlier in this paper. Bare and Field observe that the incorporation of probabilistic components in the already large FORPLAN models would lead to models that may be unsolvable given current state of the art solution techniques and computing capabilities. They also express the concern that a single criterion of optimality implies that there is a single decisionmaker. Sensitivity analysis is suggested as one approach to dealing with the problem of uncertainty while multi-criterion optimization techniques (Cohen and Marks 1975, Steuer 1986) are alternatives that address the single-criterion problem. Investigation into how to apply these techniques to forest planning applications is suggested. Bare and Field conclude their discussion by pointing out that while LP's limitations are significant, there exists no other modeling technique without similar limitations. The greatest danger, in their opinion, is that users of any modeling technique may not understand its limitations and think it functions better than it really does.

Bare and Field next turn their attention to the question of how well FORPLAN as an LP works. They conclude that the most serious problems--model understandability, analysis costs, and lack of resources to conduct sensitivity analyses--all arise from the formulation of models that are too large. While some of these problems have been addressed in part (Kent et al. 1987) much remains to be done.

The question of whether or not FORPLAN as a model is the right technique and is correctly used in forest planning applications, is addressed next. In answering this question, they focus on two closely related points:

1. the complexity of both the FORPLAN system and the models generated with it can allow for data errors and hidden assumptions to go undetected, and

2. problems that arise from the violation of LP's assumptions.

The second point and its implications have been discussed above. An important consequence of the first point is the fact that results can be obtained that are at least hard to interpret or explain and in fact can be misleading. Bare and Field conclude that many of these problems arise from the perceived need to include everything in one giant LP model following the rational-comprehensive philosophy. They recommend that the planning process be examined and suggest that a multi-stage approach (see also Mitchell 1986) might be more logical and understandable.

Attention is then turned to a third question--are the results obtained from FORPLAN models useful for forest planning? On the positive side they point out that FORPLAN has been useful as an accounting tool; that it has in some cases provided insights leading to "novel and defensible recommendations for National Forest Management;" that benchmark analysis also facilitated the development of insights and served to partially fill the gap left by incomplete sensitivity analyses; and that the

"future benefits to natural resource management" obtained from experiences with this first round of planning may be substantial. On the negative side they suggest that inadequate sensitivity analysis was conducted because "the models were generally too large, the time too short, the computing budget too small, and the analytical skills too limited." They also express the concern that there was "no clear understanding of the relationship between analysis and decisionmaking." A closely related problem in their opinion was that "failure to do real analysis or failure to recognize the distinction between insights and answers probably led to many unsupportable decisions based on invalid FORPLAN results."

Many of these problems, such as the need for more training, etc., are institutional in nature. However, the root of some seems, once again, to be large, expensive models which result from what might be viewed as an "all the eggs in one basket" approach suggested by rational comprehensive planning, and this does suggest research priorities as has already been pointed out.

Bare and Field next address the dual questions of why is FORPLAN an LP and what were the alternatives in 1979? We will not consider this discussion in detail except to observe that they conclude that "Forest Service analysts were justified in selecting LP as their prime 'mathematical apparatus' to drive the forest planning." They go on to qualify this by stating that in their opinion, while this decision was sound when one reviewed the planning tools that were available:

> "The major flow rested with the decision and (yes) the desire to satisfy the need for comprehensive analysis by building and solving a single, large scale LP model with thousands of rows and tens of thousand of columns. Apparently, insufficient thought was given to two fundamental questions: (1) Was the model to be used to guide strategic, tactical or operational planning? and (2) How relevant would model results be to on-the-ground managers and how easy would it be to explain model outputs?"

Bare and Field conclude their paper by suggesting alternatives to LP and FORPLAN and by outlining a procedure that the agency might follow in order to prepare for the next round of forest planning. We will discuss the two in reverse order to emphasize the point that broader questions pertaining to the planning process and the role of analysis must be answered before attention can be turned to the choice of analysis tools and procedures.

Bare and Field suggest the following 4-step procedure:

1. Evaluate the accomplishments/failures in planning
   a) Consider expected futures for the agency
   b) Examine the use and success of planning in other organizations.
2. Propose a new framework for Forest Service planning
   a) Recognize the changing philosophies in planning
   b) Recognize that planning is the continuous technique of adapting the organization to its environment
   c) Make every effort to integrate planning with management
   d) Do not let planning tools drive the development of the framework
   e) Recognize the rapidly changing computer technology
3. Specify the analytical support that will be needed to implement planning within the framework
   a) Include the level of administrative support that will be needed including authorizations for hardware, software, maintenance, development of analytical skills of users, and managerial time to link closely with planners and analysts.
4. Develop the necessary planning support system.

A number of both institutional and research priorities are clearly suggested.

Bare and Field also suggest a number of alternatives to FORPLAN in doing planning analysis. They make the point that all of these will most likely be more effective if the hierarchical nature of planning is recognized and separate models are utilized at each level. Among the mathematical programming approaches suggested are LP model reduction techniques (Navon et al. 1986), decomposition (Hoganson and Rose 1984), and multiple criterion optimization (Allen 1986, Bare and Mendoza 1987). Approaches that combine simulation and optimization (Hoganson and Rose 1984, Holling et al. 1986) may prove useful. Finally, they note studies that utilized LP (Hay and Dahl 1984, Hof and Pickens 1987, Weintraub et al. 1986) where the hierarchical nature of planning was recognized and large overly complex models were avoided.

We now turn our attention to the two discussion papers (Dykstra 1987, Navon 1987). Dykstra indicates that, for the most part, he agrees with the technical aspects of the Bare and Field evaluation. He does identify three concerns that need further consideration: data errors, the definition of analysis areas, and hierarchical or multi-level planning.

He distinguishes data entry errors from the more serious errors of measurement and classification. Measurement errors are identified as an especially serious problem for nontimber resources. In many cases, appropriate measurement procedures have not been defined for these resources. This can result in assessments with large measurement errors being used in FORPLAN models which in turn results in flawed FORPLAN analyses. Dykstra points out that this would be a problem regardless of the analysis approach utilized.

Clearly, additional research is needed in this area. It is to be hoped that the results of the first round of planning will be used to help identify the most critical data needs and thus aid in setting research priorities.

Dykstra goes on to suggest that data classification errors, unlike measurement errors, may result from FORPLAN analysis itself. As an example of this, he notes that different forest planning staffs have chosen different approaches and assumptions for defining analysis areas. In particular, some forests use contiguous nonhomogeneous analysis areas while others use noncontiguous homogeneous (traditional) analysis areas. He concludes that FORPLAN results, especially present net value calculations, can be significantly influenced by this choice. The question is which, if either, method of definition reflects how the forest is actually managed? This question needs resolution because, if an incorrect method is chosen, FORPLAN (or any other planning tools) results may be flawed.

Dykstra makes another observation concerning analysis areas. That is, different resources may require different definitions of analysis areas. As an example, wildlife do not necessarily concern themselves with the vegetative boundaries that have been one of the traditional parameters considered in analysis area definition. He suggests that to properly consider sets of overlapping analysis areas will require the use of a geographic information or similar system.

Dykstra's last concern relates to the question of hierarchical planning. He agrees with Bare and Field's conclusions but feels that their recommendations (as strong as they are) don't go for enough. He proposes a three level planning system with strategic planning (allocation) being conducted at the national level, tactical planning (scheduling) being conducted at the forest level, and operational planning (implementation) being conducted at the district level. The level and type of detail should vary as appropriate, with each level. For example, strategic planning does not require the type of detail needed to manage a forest while operational planning should be site specific and should have spatial integrity. He does not, however, specify any particular tools or analysis procedures that might be utilized. He does indicate that the multilevel optimization work of Hof and Pickens (1987) is an example of how this approach might be implemented.

Navon (1987) in the other discussion paper, takes a somewhat different approach to his evaluation, although he comes to many of the same conclusions. He begins by noting that, with a few minor exceptions, he is in agreement with Bare and Field's analysis. He then proposes a framework for evaluating computerized systems for planning. This framework addresses three sets of criteria:

1. is the system sound, i.e., is it free of logical and programming errors,
2. is it operational, i.e., can it be or has it been used correctly and cost-effectively in planning, and
3. is it relevant, i.e., does it or can it meet institutional requirements and information needs?

This framework is used to extend Bare and Field's evaluation of FORPLAN. Much of his evaluation addresses topics specific to the computer software and its documentation. These will not be discussed since, while important, they are not research-related. With regard to FORPLAN and how it has been used, Navon raises many of the same concerns as do Bare and Field. These include problems with model size and complexity, model cost, difficulty in conducting sensitivity analyses, and problems arising from uncertainty.

In some areas, he focuses on concerns beyond those which were addressed by Bare and Field. He is particularly concerned about the implications of the assumptions of LP (a concern that he feels is all the more serious because of the size of FORPLAN models). He suggests that these implications should be evaluated to establish whether an acceptable level of realism can be reached using LP. He is also concerned about the implications of poor quality data on FORPLAN results. Inputs and outputs should not be included in FORPLAN models if reliable data on them are not available. He, like Bare and Field, feels that an evaluation of all aspects of the first round of planning needs to be conducted.

Despite these problems, Navon arrived at somewhat different conclusions about FORPLAN. He feels that the system has addressed Forest Service institutional requirements but, because of the problems mentioned above there are questions about the adequacy and reliability of the information provided. He does feel however that there are no attractive alternatives to FORPLAN available. Rather, the solution to the dilemma is to restructure the way in which FORPLAN is used.

Towards this end, he recommends, like Bare and Field and Dykstra that comprehensive site specific planning be replaced with a hierarchical approach. He goes on to outline an approach which may alleviate many of the problems outlined above. His approach differs from Dykstra's in two important ways. One, it would involve the use of FORPLAN as the central analysis tool. While Dykstra did not preclude the use of FORPLAN, he did leave the question of analysis procedures open. Secondly, while both system contain three steps, in Navon's system, all three would take place at the forest and district level, while Dykstra's proposal included one planning step at the national level. Of course, there is nothing to preclude the addition of a fourth step to Navon's system that would relate to National Level planning.

The implications for research arising from Navon's recommendations are much the same as those discussed in the context of the previous papers and, therefore, they will not be repeated.

CONCLUSIONS

Perhaps the most interesting conclusion to draw from this review is the consistency with which certain research problems were identified. This is especially interesting when the diversity of participants in the two meetings is considered. We group these problems into one of two categories, basic and applied,

and then briefly identify some of the more important ones in each category. Important problems in the first category include:

1. A more complete characterization of the agency's overall planning process needs to be developed.
2. Once item 1 is completed, the role of forest planning, and the role of analysis can be more clearly defined.
3. With the planning process and the role of forest planning characterized, attention can be turned to an identification of planning strategies (i.e., rational comprehensive vs. hierarchical) and the role of analysis in planning.
4. The choice of analysis tools must then be considered and new systems must be developed or existing ones modified as appropriate. Necessary linkages between systems must also be identified and developed. This work must take into consideration the need to better incorporate nontimber resources, spatial concerns, and uncertainty in planning analysis. Throughout all of these investigations, the need to make planning and analysis understandable to interested parties both in and outside the agency must be kept in mind. Necessary linkages between different levels of planning must be developed and at all times the underlying goal of improving management and decisionmaking through planning must be kept in mind.

Among the more important applied problems are:

1. Critical data needs for planning and analysis must be identified and satisfied.
2. Our understanding both of how to implement plans and utilize the results of implementation to facilitate the next round of planning must be improved.
3. A better understanding of the implications of budget levels on planning must be developed.

While this paper has focused on problems with the first round of planning, we must point out that much has been accomplished. It is also clear that the problems surfaced during the two meetings are difficult and will be challenging to address. As is often the case, the difficult problems are the last to be resolved.

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Applications of Markovian Decision Models in Forest Management

Joseph Buongiorno and Ismail Kaya[1]

Abstract.--Markovian decision models represent a practical approach to decision making under risk in forest management. Very complex stochastic systems models can be reduced to simple transition probability matrices that constitute the core of a Markovian model. Optimization techniques can then be used to find the best management strategy. The method will be illustrated with an application to selective cutting in northern hardwoods. The results suggest that Markovian management guides could increase returns considerably, compared with either traditional guides or deterministic models.

Risk is an inescapable element of decision making in forestry. Risk arises within the forest itself, and in its environment. Our knowledge of the biological growth of forest stands is still imperfect. We can only tell very roughly how trees will grow, and even if we could tell, that growth will always be subject to the vagaries of the weather. Unfortunately, chaos theorist have demonstrated that accurate long-term weather forecasting is impossible (Grebogi et al. 1987). Even worse is our inability to forecast the environmental variables that bear upon forest decision making. Take as a simple example the case of timber prices. Forecasting them, whether in the short or long term, seems a very difficult endeavor. One that is most likely as unattainable as weather forecasting.

The consequences of this situation seem inevitable. Risk should be taken explicitly into account in formulating forest management policies. This is a situation that has been recognized very early by some pioneer of forest modeling. For example, Gould and O'Reagan (1965) in their forest simulator used a stochastic function to simulate random fires. It is easy to show that when such catastrophes can wipe out forests, the best decisions (for example the choice of a rotation) are quite different from those provided by deterministic calculations (Buongiorno and Gilless 1987, chapter 15).

Nevertheless, few studies have attempted to devise optimum forest management policies in the case of complex systems involving several decision variables. One early exception was Hool (1966), who was the first to suggest a Markovian decision framework. He applied it to even-aged plantations, to maximize the volume produced within a finite time horizon. Hool's work was followed by that of Lembersky and Johnson (1975) who used the same principles to maximize the soil expectation value of Douglas-fir plantations in the Pacific Northwest. Lembersky (1976) modified the model to maximize the annual volume produced, also with a infinite horizon.

Few Markovian decision models, in forestry or other fields, seem to have been implemented (White 1985). This is surprising. Markovian decision models are conceptually simple, they are easy to solve, and if the state variables are well defined, the results are easy to apply. We shall try to illustrate this simplicity and power with a recent application of the method to uneven-aged management (Kaya and Buongiorno 1987).

Basic Concepts

The core of a Markovian decision model is a matrix of probabilities p(jli,k) giving the probability that the system of interest (let us say a stand of trees) ends in state j after a certain time interval, given that it starts in state i and that the decision k is made.

This probability depends only on the starting state and on the decision, regardless of the past history of the system. This Markovian property is not really a serious limitation because the states can always be defined so that the property is very closely verified.

Associated with the transition probability matrix is a return matrix $r_{i,k}$ that gives the immediate return obtained from the system in state i when decision k is made.

The objective function may vary. Throughout the remainder of this paper we shall assume that the manager's objective is to maximize the expected total discounted value of the returns, over an infinite horizon.

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The problem then is to define the optimum policy, that is the best way to make every decision. It has been shown (e.g., Howard 1960) that among all possible policies there is at least one stationary policy that is optimal. A stationary policy assigns one single decision to each possible state.

In the following sections we shall discuss the choice of system states, the computation of transition probabilities, and the determination of an optimal solution in the case of uneven-aged forest management.

Choice of System States

Development of a successful Markovian decision model requires careful definition of the system states. In the case of uneven-aged stands, the definition of a state must be simple so that it is easily implemented in the field. Nevertheless, it must allow for a wide array of management regimes.

In our system each state is defined by a combination of a stand state and of a market state. The market state is defined simply by the level of product prices, which may be high, medium, or low. Stand states are defined by the amount of basal area in three product classes: pole timber, small sawtimber, and large sawtimber. For each product class we defined five levels of basal area, from "very low" (0 to 10 square feet of basal area) to "very high" (75 square feet of basal area or more).

Computation of Transition Probabilities

One of the most difficult parts in building Markovian decision models is the choice of transition probabilities. Recall that this is the probability that the system moves from one state to another, when a particular decision is made.

In the case of uneven-aged management, a decision consists simply of doing nothing, or of cutting the stand from a particular state to another, by reducing the basal area in one or more of the three product classes. Then, each transition probability is the product of the stand transition probability (probability that it moves from one state to another) by the probability of a particular product price level. This is so because prices are independent of stand states, and in efficient markets, prices are uncorrelated over time (if they are not, this can be easily taken into account).

The main task, then, is to determine the transition probabilities between stand states. This is usually difficult to do from direct observations (for example from permanent sample plots). There are simply not enough observations to cover all the stand states that may occur in actual management.

A practical alternative is to use stochastic simulation. In the case of uneven-aged management, several stand models exist that give not only the expected value of stand growth, but also some measure of the variability around that expected value. In the best cases, not only are the standard errors available, but also the variance-covariance matrix of the residuals (Michie 1981). Then, for each time interval, one can compute the deterministic component of growth, and add a stochastic part by sampling from the multivariate distribution that describes best the residuals of the model.

This kind of simulation can be used effectively to count the number of passages from a stand state to another, when a wide variety of harvests are applied to the stand (random harvests will do, the idea being to make sure that during a simulation the stand visits as many possible states as possible). Then, a summary count of the relative frequencies of passage from one state to another gives the desired probabilities. Those states that occur very rarely can be omitted, thus reducing considerably the size of the problem.

This simulation technique is a practical way of "bringing the real world to the laboratory" (Holling et al. 1986). In effect, this procedure condenses the information contained in a possibly complex simulation model into a simple transition probability matrix to which powerful optimization methods can be brought upon to compute the best policy.

Determination of Returns and of Best Policy

In our system the basal area cut in each product class at decision time is the difference between the basal area before and after harvest. From this and other information on stand state and costs of harvesting, one can determine the value of the cut, that is the immediate return, when a particular combination of stand and price state is observed, and when a particular decision is made.

This transition probability matrix, together with the matrix of immediate returns provides all the information needed to compute the optimum policy. Several approaches are possible to do the computations. They include linear programming (d'Epenoux 1963), policy improvement algorithms (Howard 1960), and successive approximations (e.g., Ross 1970).

Successive approximations seems to be by far the best approach. It does not require the solution of a large system of simultaneous solutions at each iteration. Thus, quick solutions of very large problems are possible on a microcomputer, using successive approximations . Like policy improvement, but unlike linear programming, this method gives besides the optimal policy, the stand value (i.e., the discounted value of future returns when the best policy is followed) in function of the initial state. Best of all, successive approximations is conceptually straightforward. It consists in solving the following recursive equations:

$$V_i^{t+1} = \underset{k}{\max} \left[r_{i,k} + d\Sigma_j p(j|i,k) V_j^t \right] \text{ for all } i$$

where V_i^t is the expected discounted value of returns from initial stand-market state i, managed optimally for t periods. The discount factor is d.

This equation says that the best decision at time t must maximize the sum of the immediate returns and of the dis-

counted value of the returns generated earlier by following the optimal policy.

The method of successive approximations consists of applying the above equations, starting from arbitrary values of V_i^0, say zero, and increasing t until V_i^t converges. The limit of V_i^t as t increases to infinity is the discounted value of the returns from the stand, given the initial condition i, when the optimum policy is followed. Thus it is the stand value, inclusive of initial growing stock and land.

Results and Implementation

The main results of a Markovian decision model can be summarized by a decision table. In our case that table gives the best decision (stand state after harvest) for each combination of stand and market state (price level). Because the optimal policy is stationary, that decision table is unique; in particular, it is independent of the initial stand state. Because state variables are easy to measure in the field, such a table represents a practical harvesting guide.

In contrast to the harvest policy, the stand value depends very much on the initial condition of the stand and of the market. As seen above, this stand value is a by-product of the method of successive approximations. This information can be extremely useful for forest valuation. It is also useful in comparing a Markovian cutting guide with others.

In the case of northern hardwoods management we found that stand values obtained by applying a Markovian cutting guide were much higher than those yielded by the traditional Lake States cutting guide. They were also generally superior to those obtained with a deterministic optimization model (the gain varies with the initial condition of the stand and market, see Kaya and Buongiorno 1988).

Within the framework of a Markovian model, the cutting cycle is a random variable; a stand is not necessarily cut every time it is examined. Similarly, the amount of timber cut, and the corresponding residual basal area, are random variables. They vary depending on the price level and on the state of the stand. Nevertheless, one can from the solution determine the expected cutting cycle, the expected value of the cut, and the expected residual area after the cut (Kaya and Buongiorno 1987). Thus, all the information available from classical harvesting guides can also be obtained from the solution of a Markovian decision model.

Conclusion

Markovian decision models should have great potential in forestry decision making. They represent a simple, yet general, way of recognizing elements of risk in the outcomes of decisions. From our experience in uneven-aged management, policies developed from Markovian decision models may be quite superior to those computed by deterministic models.

The core of Markovian decision models consists of a transition probability matrix that can be obtained by stochastic simulation. The simulator serves to "bring the real world to the laboratory" (Holling et al. 1986), and the simulation experiments are summarized compactly in the transition probability matrix. Then, efficient solution algorithms can be used to obtain the optimum policy. This seems a better way of finding a policy than exploring the response surface of a complex simulation model.

The resulting policy is stationary: to a state of the system, regardless of when it occurs, corresponds a single best decision. As such the policy is very simple to apply, as long as one takes good care to define system states that are easy to recognize in practice. The policy does not need to be recomputed frequently, only when significant changes have occurred in the distribution of price changes, or in the growth of stands.

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A Comparison Between Timber Harvest Projections for a Northwest Forest Solved Using Model II Linear Programs on a Micro and Mainframe Computer

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Abstract.--This paper compares results between two Model II linear programs used for timber harvest analysis on an industrially managed forest in the Pacific Northwest. One model was run on an IBM PC and the other on an IBM mainframe. The mainframe model was the MUSYC model developed by the U.S. Forest Service. The micro computer model was written by the author for solving the given harvest analysis problem. The timber harvests projected were within a few percentage of each other, both on the base case run, and for numerous sensitivities. The mainframe model had the ability to provide a more detailed solution. The micro computer model provided a similar result, however, with no time share charges, and may be a more realistic representation of the timber harvest pattern to evolve on the ground. Model selection depends on the level of detail desired by the decision makers, and the personnel and computer resources available. It may also be a good strategy to build both models as was done in this case. The micro computer model was used often to perform low cost and fast turn around sensitivity analysis after it was established as a tool which provided accurate solutions.

All forest land owners make decisions regarding timber harvest rates over time. Much of forest management is related to this decision as desired harvest levels effect reforestation and stand management decisions. In the past such decisions were often based on volume or acre formulas. With the increased use of computers, these decisions have been analyzed using computers. Organizations such as the USDA Forest Service, a number of state agencies, and many large timber corporations now use large linear program models for assessing alternative harvest patterns (Davis and Johnson 1987). Small organizations may not have access to this computing power but typically may have access to micro computers. This paper presents comparisons between results gained from both a micro computer model and a mainframe model for a forest tract in excess of 100,000 acres.

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The mainframe timber harvest scheduling model used was the Multiple Use Sustained Yield Calculation (MUSYC) model developed for the U.S. Forest Service (Johnson and Jones 1979). This model consists of a matrix generator and a report writer which is run in conjunction with a linear program solving package. MUSYC builds the matrix, feeds this matrix into the linear program solver, and then interprets the linear program output giving both detailed and summary information. The micro computer model was constructed by the author using the LPX88 linear programming package from Eastern Software Products[2] (1985).

There was no deliberate plan to run both a micro and mainframe timber harvest model, rather it evolved as step in the

[2]*The use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of a service or product by the U.S. Department of Agriculture to the exclusion of others that may be suitable.*

timber harvest planning process. An evaluation of sustainable timber harvests was being performed for all timberlands divisions within the company; the forest under study was one of the areas covered in this program. The company was using either MUSYC or FORPLAN (Johnson 1986) to do these analyses. The steps for doing the analysis were the standard ones of aggregation of stands into stand types, projecting the yield and value over time, and putting this information into a LP to maximize an objective while meeting a set of constraints.

The company's timber inventory was an in-place, type map inventory. Reinventory was an ongoing process so the years since last inventory for a given stand was variable. The records were maintained in a custom data base on a 16 bit minicomputer. Because of the slowness of this machine and the lack of appropriate software, the relevant inventory information was uploaded to the mainframe computer to stratify timber stands for aggregation into stand types. In excess of 2,000 timber stands were recognized in the forest inventory. Using the Statistical Analysis System[2] (SAS), the stands were stratified by age, species, site, and stocking. Five-year age classes were recognized, except that all stands over age 65 were merged to the oldest age class.

The four species grouping were Douglas-fir, Hemlock, Mixed, and Hardwoods. Stands with less than 60% of their growing stock in Douglas-fir, hemlock, or hardwoods were considered mixed stands. Site quality was initially divided into to four classes. If too few acres resulted after this stratification process, site classes were merged so that in most cases, only two classes were recognized: good sites and poorer sites. Stocking was also divided into four classes, but after further aggregation to meet minimum stand type acreage guidelines usually only two stocking classes remained. Aggregations containing less than 200 acres were further merged with the most similar existing stand type to create stand types of at least 200 acres.

The result of this stratification process was about 120 stand types which were to be used in creation of the decision variables of the models. For each stand, the number of acres, number of trees, and average diameter by species class, site index, and age was computed. Each stand type was projected over time in 5-year increments using a modified version of Arney's (1985) Stand Projection System[2] (SPS). The SPS modifications were in the log bucking and scaling routines. In addition, the model was modified to calculate the economic value of the stands. The projected timber yields, harvest costs, and harvest revenues were input into the Smart Data Manager[2] (Innovative Software 1986) to be available for reporting in various ways.

This process was completed before it was time to run the MUSYC model so the author decided to undertake a preliminary analysis of the sustainable harvest by building a small linear program. The construction of this small model was seen as a process that would help determine if there might be any hitches in the model construction of the MUSYC model. We wanted to be apprised of any problems while we still had time to solve them.

Construction of the Micro Computer Timber Harvest Model

The goal of constructing the micro computer model was to give a preliminary estimate of the sustainable harvest of the forest. The linear programming (LP) software program that we had, LPX88, is capable of solving a sparse matrix of about 500 rows and 1,500 columns. We were using a two-diskette drive, IBM PC for solving the matrix. We decided to keep the model small to minimize its construction and solutions time. To retain what we deemed the most important information, we decided to aggregate the results across species, site, and stocking, so all that remained were 10 timber types of the various ages, plus an additional three types for representing severely understocked stands. All regenerated stands were merged into a composite stand representing our best estimate of the average yields and values we expected regenerated stands to provide. We used the Smart Data Manager to implement the merging, thus the merging of stands was completed after the growth projection had been done. The timber yields in the micro model would thus be the same on average as the yields from the MUSYC model.

Each stand type (existing and regenerated) was allowed as a harvest candidate at age 45, 50, 55, and 60, except that all existing stands were allowed at least three future periods for harvest. Twenty, 5-year periods, or about two rotations, were used as the modelling time horizon. A series of decision variables that represented the harvest options for current and regenerated stands and the periodic harvest definitions made up the columns of the matrix. Constraint rows were the harvest definition rows, the Model II regeneration transfer rows, the acreage constraints, and the harvest flow constraints. Model size was about 100 columns by 85 rows. The objective function was to maximize the discounted timber harvest. As long as all timber volume had the same per unit value, then this would approximate the maximization of net present value which was the firm's objective. This was accomplished by simply putting the appropriate discount factor for each period into the objective function row of the harvest definition variables.

The linear program was solved and a series of sensitivities performed. The model took about 45 minutes to solve with the previously described computing system. I have subsequently solved the model on an IBM AT compatible computer (Zenith Z-241 series) with numeric data coprocessor and RAM disk in about 5 minutes. Initial harvest projections were for a non-declining harvest, and a modulated harvest flow that allowed a decrease of 1% per year (5% per period), or an increase of 2% per year. A 5% discount rate was used.

The non-declining solution showed a constant cut for eight periods at which time the currently managed young plantations provided a source of higher harvests. The modulated flow had a higher first period harvest which then declined at the maximum allowable rate for eight periods before beginning an increase which was followed by another decrease cycle. The discounted cut was about 3% lower for the non-declining harvest. Studying the decision variables demonstrated that the

model was generally choosing stands in order of their age, that is, oldest stands were cut first, then the next oldest, and so forth. After examination of the preliminary solution, several sensitivity tests were requested to evaluate the concerns of the forest managers.

Sensitivity runs investigated the effect of a higher discount rate (7%), the effect of lower yields on regenerated stands, the effect of a 10% lower growth rate, the effect of separating the two major operating units within the model (the opposite of an allowable cut effect), and the effect of a lower initial starting inventory on some stands for which there was a concern the inventory information was less reliable. The increase in the discount rate had no effect on the harvest flows. In other words, timber harvest constraints were more important than the discount rate. Likewise, lowering regenerated stand yields had no effect for the first 40 years of the model. It simply meant that future yields would be lower. A 10% decrease in the growth rates decreased the initial cut for non-declining yield by about 3%, and somewhat more for the modulated flow. Decreasing initial stand inventory on some stands decreased the initial harvest slightly. At this point, there was a sense that the harvest flow capabilities of the forest had been fairly well identified.

Construction of the MUSYC model

The next phase was the construction of the MUSYC model. The data base manager was used to print out files of timber yields, and harvest cost and revenue data. These files were then uploaded to the mainframe and merged into the MUSYC input file. All 120 stand types were listed individually. A single regenerated stand table, as used above, was also included in the MUSYC input.

After trouble shooting the MUSYC model it was then solved with the same harvest constraints used above. The objective was to maximize net present value, but in this case the harvest costs and revenues from each stand type were used to generate the NPV. Also, a higher discount rate was used. The resulting harvest flow, however, was within 3% of that projected by the micro model discussed above.

The nature of the MUSYC solutions, however, were much more specific, and also quite different. Whereas the micro model chose stands on the basis of their age, the MUSYC model went after value. It first harvested the Douglas-fir in the most valuable unit, then harvested the Douglas-fir in the other units, then the hemlock in the most valuable unit, then the hemlock in the other units, and finally hardwoods. This solution could be predicted for an optimization problem operating under a high discount rate. This solution, however, was not deemed operationally feasible.

The next stage in the MUSYC planning process was to determine ways to place constraints on the model to yield solutions that were deemed operationally feasible. Harvests could not be concentrated on one unit due to both log flow concerns at the mills, and watershed values of the forest. The mills were not interested in a continual shifting of species. Operationally it was also recognized that logging settings include some less desirable acres along with the good ones. A further problem was that the high discount rate caused the model to harvest extremely young stands for harvest, stands for which the trees were not of a large enough size for the profitable running of the wood products converting plants.

A set of additional constraints was added to the MUSYC model to recognize these operational realities. Limits were placed on the amount that could be harvest in any unit in each period. Limits were also placed on the species mix to ensure that changes in the mix were at an operationally feasible level. Poor quality timber stands were forced into the solution. Because piece size constraints were not a part of the MUSYC model construction, harvest age was constrained to be not less than 50 years to insure that minimum piece size requirements were met. The model was then resolved, with similar harvest flows resulting, but with different choices of stands to be harvested over time.

Some of the same sort of sensitivity results as had been done on the micro model were also done on the MUSYC model with essentially the same results. Additional sensitivities that could be run were sensitivities to an increase or decrease in timber prices. A 10% increase or decrease in timber prices had no effect on the solution (other than the reported NPV). We were also able to determine at which discount rate the model would choose to build growing stock rather than harvest as much as possible as fast as allowed.

The micro model was then amended to reflect any changes that could be placed into its structure. The biggest change was restricting timber harvests to stands 50 years or older. The micro model was then resolved and the results compared. Figure 1 shows the difference in harvest flow predicted by the two models when under a non-declining flow constraint. The solutions are within about 1% of each other. Figure 2 compares the results when harvest are allowed to decline up to 1% annually, but may double between periods. The solutions are within a couple of percent until the recent plantations and regenerated stands come on line, at which point they diverge.

Discussion

The results presented here have demonstrated that, at least for the forest shown here, the harvest flow results are essentially the same for the MUSYC model and the micro model. While this is only anecdotal evidence for a general claim, it may hold for many forests. Johnson and Tedder (1984) note that for straightforward problems, binary search will provide the same solution as a detailed linear program. In special cases, the large linear program solution can reveal insights not gained in binary search. Although this is a comparison of linear program to linear program, the MUSYC model certainly represented more detail and may for certain forest structures yield a fairly different result than could be obtained using a micro model.

For a manager trying decide which approach to use for determining appropriate harvest levels I offer the following insights:

1. There may be no choice. Smaller landowners may have neither the computing nor human resources needed to use something like the MUSYC model. Public land managers, or private managers operating in centrally controlled firms, may be administratively constrained to using such models. For the those not in one of the above categories, it probably makes sense to use the one which is easiest. As noted above, the initial steps in forest planning are the same, regardless of the modelling approach chosen. Those steps are stratifying the forest land into homogeneous timber classes and predicting yields and values. These projections over time must then be interfaced with the harvest analysis model. When the harvest analysis model is an LP, one constructs an LP that describes the growth and cutting options available on the forest.

The degree of effort required to build and analyze the results of either model depends on the background of the user. The MUSYC model has extensive documentation on how to prepare the input and use the model. Those not familiar with the model would have to invest a lot of time to learn its operation. The micro model, on the other hand, requires construction of the linear programming matrix and interpretation of the results. No summary information is presented on the output. For someone familiar with linear programming, it would probably be faster for him or her to set up, run, and interpret a micro model than to learn how to use the MUSYC model. For someone without the knowledge to set up a linear program model, use of a model such as MUSYC would probably be faster than learning about linear programming. Linear programming for use in timber harvest scheduling is now taught at most forestry schools, though usually only the top undergraduates gain a working knowledge

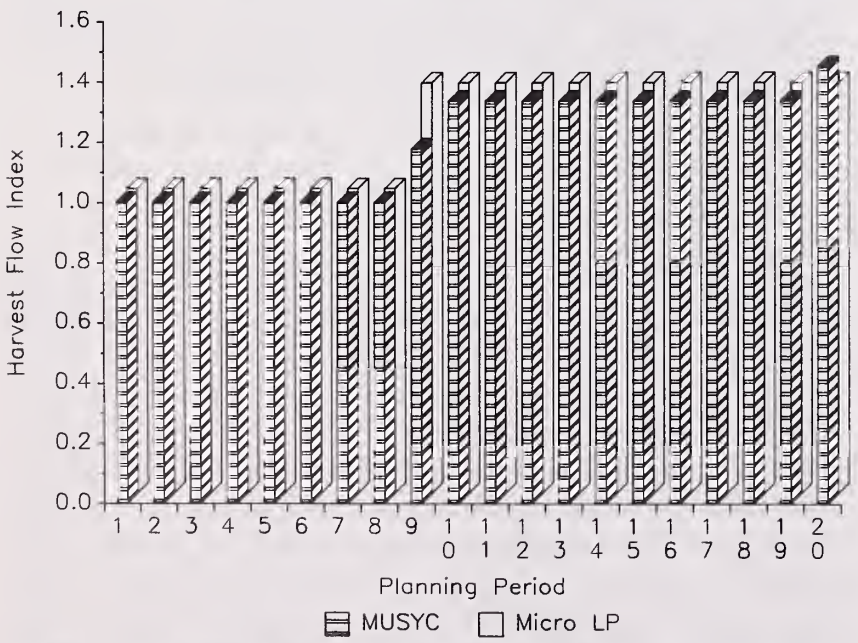


Figure 1.--The harvest flow projected by the MUSYC model and the micro model under non-declining harvest flow constraints.

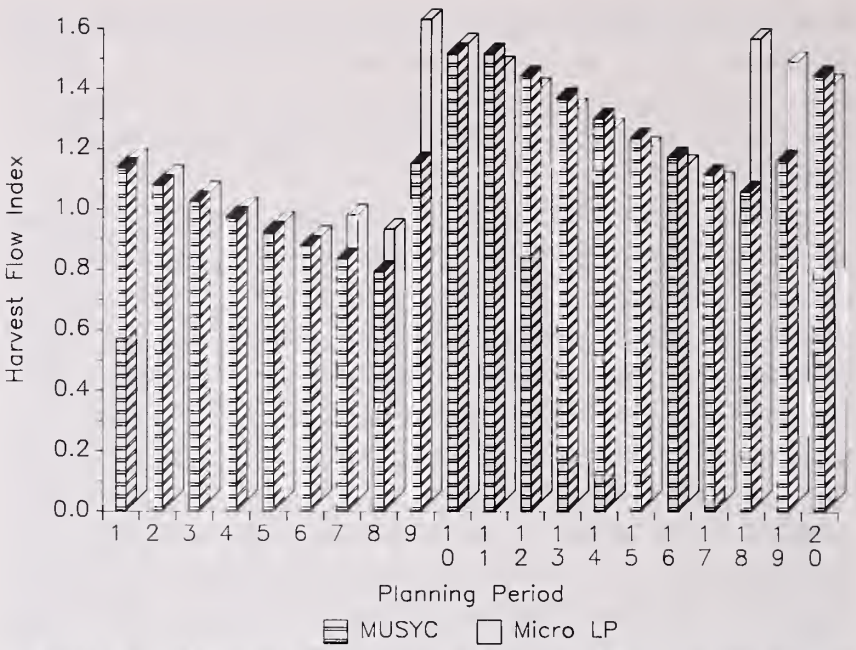


Figure 2.--The harvest flow projected by the MUSYC model and the micro model under modulating harvest flow constraints.

suitable for setting up their own linear programs. Graduate students studying forest management or quantitative analysis would gain the requisite modelling skills.

Time share computer charges are probably less important than human resources cost in which ever solution is chosen. The MUSYC modelling effort was probably charged $2,500 to $3,500 of time share charges. The human resources cost in setting and run the model was no doubt more costly than computer time charges. The linear program software for the micro computer cost under $100, and added no further computing cost. MUSYC models were typically run at low priority over night to keep their cost down. The micro model was often run over lunch hour to not tie up the micro computer.

2. It depends on the amount of decentralization in decision making. For a firm that wants to centralize decision making and provide control over practices in various divisions, a large scale model with central expertise for constructing and running of the model can ensure greater consistency than if each division were to construct its own.

3. What is possible on the ground? The biggest problem with the initial runs of the MUSYC model is that the solution would not be implemented. Even if the solution could have been implemented, those doing the day to day management would manage a solution they were comfortable with. The MUSYC model provided more detail than could probably be executed on the ground. One could argue, of course, that the MUSYC model should have recognized fewer, or perhaps a different sort of, decision variables to provide a more realistic solution. The micro model provided a more general solution that proposed to cut in relationship to what is out there on average--something that in general is implemented. The MUSYC model showed a penchant for early

harvest of the more valuable Douglas-fir stands. Even if only the micro model had been run, however, there would still be the tendency by the managers to seek out the Douglas-fir stands due to their greater value.

4. There is some value to running both. By constructing both models, the division was able to determine what it thought reasonable, and the corporate headquarters was able to do quality assurance of the final result. The micro model was originally set up to provide a dry run through the system before constructing the MUSYC model. We felt that going through the process would alert us to any problems that needed to be solved before the large model was constructed. In addition, it was seen as a means to verify the integrity of the MUSYC model, as any deviation between the models would trigger an investigation of both.

5. The micro model was used extensively for low cost, fast turn around solutions to various sensitivity analyses that were requested from time to time. This meant that corporate expertise was not required and the MUSYC model did not have to be retrieved from magnetic tape. The validity of the solutions to the micro model had been established by comparison to the MUSYC results. For doing the sensitivity analyses it was easier to use a micro model than the MUSYC model.

6. The anecdotal evidence of similar results between models suggests that those with a stake in the outcome of timber harvest models, but not the resources to construct an equally detailed model, could build a micro model to test the validity of the model of concern. Environmental groups, for example, could construct a small model to satisfy themselves that the public modelling results are realistic. Industry groups could likewise build small models to investigate timber supply concerns.

7. A much bigger model could have been constructed on the micro computer. Because we used only one-fifteenth of the columns and one-fourth of the rows that the software allows we could have constructed a micro model that was more similar to the MUSYC model. We also could have paid much more attention to the timber economics within the model. We did not, however, see a need to do this.

8. The primary dispute on how to manage the forest could not be solved by either model. The real issue was, which harvest flow pattern was best? No model can build in the intricacies of market fluctuations. Managers want to know the capability of the forest to produce stumpage over time, to integrate this result with the vagaries of the market in choosing which timber stands will be harvested when.

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Integrating Short-Term Spatially Feasible Harvest Plans With Long-Term Harvest Schedules Using Monte-Carlo Integer Programming and Linear Programming

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Abstract.--A procedure for integrating spatially feasible area-based plans with long-term, strata-based plans is presented. Area-based plans are generated by Monte-Carlo integer programming, and subsequently used as coordinated allocation choices within FORPLAN. The integrated plans provide spatially feasible alternatives in the short-term, and also ensure that long-term volume and net revenue flows can be sustained.

Introduction

Problem Definition

Harvest scheduling problems can be broken into two broad categories. First, there is the long-range plan that looks ahead over several rotations (150+ years), and provides an estimate of what volumes should be cut from various stands within each decade. These plans do not necessarily provide a spatially feasible solution, since the stands are aggregated over vast areas, average costs and yields are used, and individual harvesting units are not specified.

These forest wide, long-range plans are usually solved by either binary search, shadow price search, or linear programming techniques. The advantages and disadvantages of these techniques are summarized by Davis and Johnson (1987) and also by Eldred (1987). Linear programming (LP) is the most flexible method because of its ability to maximize outputs under a variety of constraints. The model formulation is based on timber strata, and is therefore referred to as strata-based planning. FORPLAN (Johnson 1987) is a widely used LP model used for long-term planning.

The second category of harvest scheduling problems deals with determining a spatially feasible solution that covers a shorter planning horizon (1 to 5 decades). Based on the harvest levels generated in the long-range LP, individual harvest units and road projects are selected for a relatively smaller area in this type of a plan. Because the problem is formulated from specific harvest units, this type of planning is referred to area-based planning. Since this approach requires integer solutions, these problems are usually solved with mixed-integer programming (MIP) techniques. The Integrated Resource Planning Model (Kirby et al. 1980) is a MIP model developed for area-based planning. Integer variables are needed for road links and harvest units to prevent them from splitting between time periods. Splitting can complicate adjacency restrictions, resulting in a situation where very small percentages of the unit are left for future periods (Moore and Nielson 1987).

Integer solutions greatly increase the computational burden of the problem, thus MIP techniques are not well suited to large planning problems. Another disadvantage of MIP is that the entire forest must be partitioned into specific harvest units, complete with planned roads and logging systems. Not only is this an enormous engineering task, but it also assumes that current logging systems and technology will remain unchanged throughout the planning horizon.

Other approaches to solving area-based planning problems include simulation and random sampling techniques. The Project Area Scheduling System (PASS) developed by Tanke (1985) for the USDA Forest Service is a simulation model designed for assessing area-based harvest scheduling problems. An important demand for this tool was the need to disaggregate FORPLAN solutions into a workable schedule of timber sales and road projects. Its major advantage is that it can quickly

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manipulate large volumes of data necessary to assess alternatives. The major disadvantage is that the analyst must provide the scheduling choices, and given the large number of possibilities, attempting to find optimal or near optimal solutions can be a difficult task (Jones et al. 1986). Tanke's work is a valuable contribution when compared to manual methods traditionally used to resolve harvest scheduling problems. When hundreds of variables and possibly thousands of alternatives are involved, arriving at just one or two feasible solutions is a major achievement.

Sessions (1987) has recently introduced a procedure in which random patterns of harvest units are generated, and then tested for adjacency constraints and harvest levels. While this procedure does not guarantee optimality, it is effective in quickly generating "good" alternatives. It is also an improvement over PASS in that the algorithm generates the harvesting schedule. Session's method uses a heuristic procedure to identify the "optimal" schedule and road network once feasible patterns of harvest units have been identified.

The situation can be summarized as follows. Strata-based planning is an efficient way to determine long-term harvest sustainability. The disadvantage is that strata-based plans may be infeasible because they lack the specific area information needed for developing operational logging plans. Conversely, area-based plans provide the information for implementing operational plans, but do not guarantee that the residual inventory structure is adequate to sustain long-term harvests.

Scope of the study

With the introduction of powerful micro computers and complementary software, it is now possible for complex forest planning issues to be dealt with at the logging division level, where the analyst(s) are more in touch with the structure, constraints, and potential of their forest. This trend will lead towards "bottom-up" planning, where the basic building blocks are spatially feasible area plans.

The time, effort, and cost of arriving at the true optimum of a MIP may not be warranted, especially when projected revenues, costs, and yields are all subject to a wide range of uncertainty. This paper proposes a method whereby managers are supplied with a number of good alternatives, thus providing them with better information and choices than does a single optimal solution. The results will provide spatially feasible alternatives that also meet long-term harvest objectives.

A procedure is presented for generating and integrating short-term, area-based plans (decades 1-3) within long-term, strata-based plans (decades 1-15). Timber production will be the only resource considered in this study. The Monte-Carlo integer programing (MCIP) technique (Conley 1980) is used to generate solutions for the 3-decade, area-based plan. These area-based plans are constrained by adjacency restrictions, volume flows, and net revenue flows. There will be no transportation network optimization once a schedule is established, because each harvest unit has only one logical route to the mill. This "tree" pattern is the result of both terrain conditions and the existing road network.

Results from the MCIP's are then used to formulate coordinated allocation choices within a 15-decade, strata-based plan, which will be solved as a linear program with the FORPLAN model (Johnson and Stuart 1987). A solution from this formulation provides a spatially feasible plan with specific yields and costs for decades 1 to 3, as well as a long-term projection of volumes and revenues for the remaining 12 decades.

The study is to be conducted on MacMillan Bloedel lands in British Columbia. The 4,000-hectare site is covered with mostly second growth timber that will serve as a long-term log supply for winter harvesting operations. Results of the study will be available in June 1988.

Objectives

There is a need to integrate short-term and long-term forest plans to ensure that both spatial feasibility and sustainable harvest goals are met. There is also a need to examine more than just one solution to the planning problem, especially in light of possible deviations from our current expectations of future revenues, costs, and yields. Specifically, the objective of the study is to identify three solutions to a 150-year timber harvesting plan that provide spatially feasible alternatives for the first 30 years, and also meet volume and net revenue goals for the subsequent 120 years. To provide for flexibility, additional spatially feasible alternatives must exist for decades 2 and 3, for each of the three integrated plans.

Methods and Procedures

There are three basic steps needed to accomplish the objective. First, estimates of long-term timber production and net revenue flows are determined. Second, harvest units are selected to form spatially feasible plans for the first 3 decades using the long-term volume and net revenue estimates as guidelines. Third, the three best area-based plans are incorporated into 150-year harvest schedules to determine their impact on future volume and revenue production.

Step One: Determining Long-Term Volume and Net Revenue Production

To arrive at our estimates of long-term timber and net revenue production, a 150-year LP is formulated using a strata-based approach. Using a Model 1 formulation (Johnson and Scheurman 1977), our objective function is to maximize present net worth (PNW), subject to the following constraints. First, a nondeclining yield (NDY) of timber that is not to exceed the long-term sustained yield (LTSY) of the forest is desired.

Second, it is preferred to have a minimum level of net revenue produced each decade to prevent the cutting of all high valued stands in the early time periods (each period is 1 decade). Third, the resulting inventory at the end of the planning horizon must be at least as large as the average inventory throughout the planning horizon. This is commonly referred to as the perpetual timber harvest constraint.

Finally, it is necessary to restrict the first 3 decades of harvesting to a specific geographic zone within the study site. Restricting the initial three-period harvest to a specific zone is needed because it would be unreasonable to plan harvesting in inaccessible portions of the forest. Using an undeveloped drainage as an example, early harvesting would be confined to a zone at the entrance to the drainage. As road construction progresses, more of the drainage becomes accessible, thus allowing more flexibility in the location of harvest units. In our example, harvesting (period 1-3) is restricted to an accessible area that contains mostly mature timber. This area is labelled zone A, and the remainder of the forest is labelled zone B. It is from within zone A that the area-based plans are generated. During periods 4 through 15, the entire forest is eligible for cutting.

The following procedure is used to determine what stands should be included in zone A. Successive LP's will be run with increasingly more hectares added to the zone until the harvest levels (periods 1-3) are not restricted by the availability of timber. Under a NDY constraint, these LP's will show an upward step in volume production after period 3 if the zone was limiting the initial cut. The point at which there is no discontinuity in the volume harvested indicates that the zone is of sufficient size, and will not be constraining the overall timber flow.

There will be approximately 70 timber strata (analysis areas) with multiple timing choices in the study. The FORPLAN model will be used to generate the linear program in Mathematical Programming System (MPS) format, and the LP software LINDO will be used to solve the problem. A typical LP formulation at this stage will have about 1,900 variables and 130 rows.

Step Two: Determining the Three Highest Valued Area-Based Plans

The results from procedure 1 will define the zone in which harvesting units are to be located. Within this zone, approximately 50 harvest units will be located. These units are designed and located to meet terrain conditions, maximum clear cut size, and logging system feasibility. Environmental policy dictates that no two adjacent units can be harvested during the same time period. Corresponding to the harvest units are about 50 main road projects and numerous secondary roads (roads and landings completely contained within a harvest unit). For the 3-decade problem, this represents around 300 integer variables [(50 units + 50 road projects) X 3 periods = 300 integer variables].

Monte-Carlo integer programming will be used to generate solutions to this area-based planning problem. The objective function is to maximize PNW subject to the volume and net revenue constraints found in the 15-decade LP, and constraints that prevent any two adjacent units from being cut in the same period. For simplicity, constraints that specify the maximum/minimum volumes of individual species are not included in the problem. Projected traffic flow over the roads will be far below capacity, so it is unnecessary to include these constraints.

There are two major methods followed to arrive at the three best solutions. In the first method, the MCIP is used to generate 200 feasible solutions (labelled temporary solutions) for the planning problem. This method, called random searches, is free to choose harvest patterns in all three periods.

In the second method, called selective searches, the three temporary solutions with the highest PNW's (TS1, TS2, and TS3) are selected for further analysis. The first period harvest pattern from these temporary solutions is fixed, and only periods 2 and 3 are allowed to vary. The two objectives of the selective searches are, first, to find better solutions, and second, to demonstrate that other alternatives exist even though the first period is fixed. This is useful information that demonstrates that flexibility is available in future periods, regardless of the action taken in period 1.

Finally, the highest valued solution found in each of the three selective searches is chosen as a "permanent solution" (PS1, PS2, and PS3), and subsequently used as a coordinated allocation choice within the integrated plans.

The random search method is described first. The MCIP algorithm is outlined in figure 1 and described below. It is basically a three-stage procedure (with each period representing a stage) in which harvest units are randomly selected for cutting at each stage. Random numbers are generated with a prime modulus multiplicative linear congruent random number generator (Schrage 1979). Random numbers are converted into binary variables (0 or 1) for each harvest unit. If a unit is assigned a value of 1, then it is to be cut in that period, otherwise it is assigned a value of 0, and will not be cut during that period.

Starting with the first period, all 50 units are eligible for cutting, so each is assigned a binary variable. The next step is to ensure that no two adjacent units are selected in the same time period. This is accomplished with an adjacency routine that sequentially reads in the binary variables for each unit. If a particular unit has a binary variable equal to one, then all adjacent units are set equal to zero. When the adjacency routine is completed, a spatially feasible pattern of harvest units has been established. At this point, the volume produced from the selected units is tested to see if it falls within the allowable tolerances. If not, we return to the start and generate a new set of binary variables, otherwise we have an acceptable solution in terms of adjacency and volume requirements, and we can proceed to the second period (stage).

The net revenue for this first period solution is not checked at this point because, through testing, it was found that fully checking each period offered no computational efficiency over

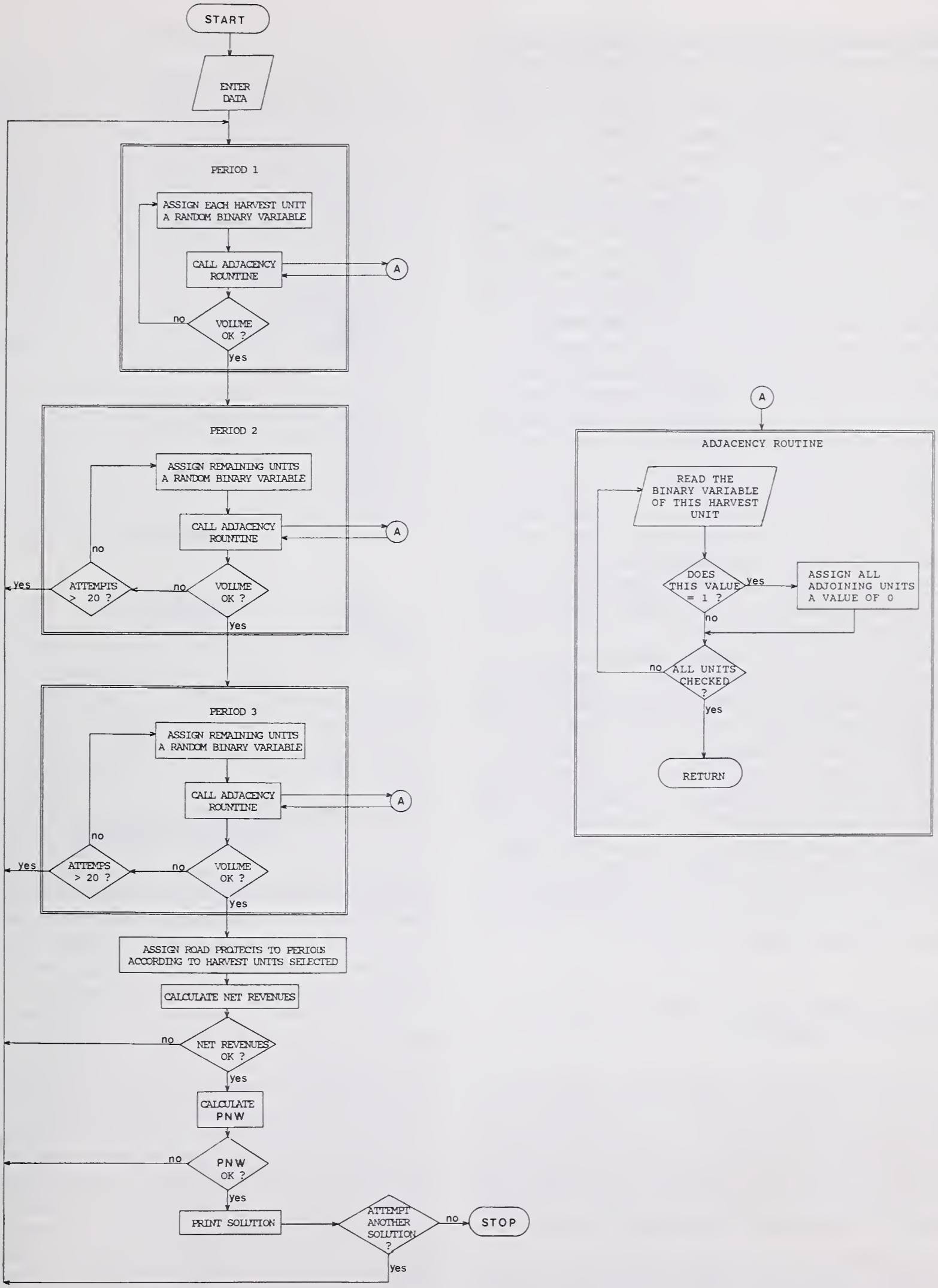


Figure 1.--Flow chart of the Monte-Carlo integer program.

checking an entire three-period solution. It takes very little time (about 1.5 seconds) for the algorithm to arrive at a three-period solution that meets adjacency and volume constraints. The minimum net revenue constraint drastically reduces the feasible region of the problem, and it takes approximately 10 minutes to generate a fully acceptable solution.

In period 2, harvest units that were selected in period 1 are no longer eligible for cutting, so binary variables are generated for the remaining units only. From this point on, the same procedures described for the first period case are repeated. If an acceptable solution cannot be found in 20 attempts, we return to the start and try a new first period solution. In most cases, a second period solution is found after about four attempts.

In the third period, the MCIP can only select units that were not cut in either of the preceding periods. If a solution can not be found in 20 attempts, we return to the start of period 1. Returning to the start of period 2, in an attempt to utilize the first period solution, failed to offer any advantage over completely starting over at the beginning of period 1.

When a feasible alternative to period 3 is found, the necessary road projects are assigned and the net revenue for each period is calculated and checked against a threshold value. If unacceptable, the solution is rejected, otherwise it is checked against a minimum PNW value. A solution that passes this final test is recorded as a feasible area-based plan (previously defined as a temporary solution).

Having completed the 200 random searches and identifying the three highest valued solutions (TS1, TS2, and TS3), three selective searches are initiated. Other than fixing the first period harvest pattern and raising the threshold PNW to eliminate low valued solutions, the MCIP algorithm operates the same way as described in the random search method. Each selective search is used to identify five new solutions. The highest valued PNW solution from each group of five selective searches is then chosen as a permanent solution (PS1, PS2, and PS3). Figure 2 illustrates how random and selective searches are used to determine the area-based plans that are subsequently used as CAC's. The MCIP will be written and compiled in Turbo Basic, and run on a Compaq Deskpro 386 computer.[2]

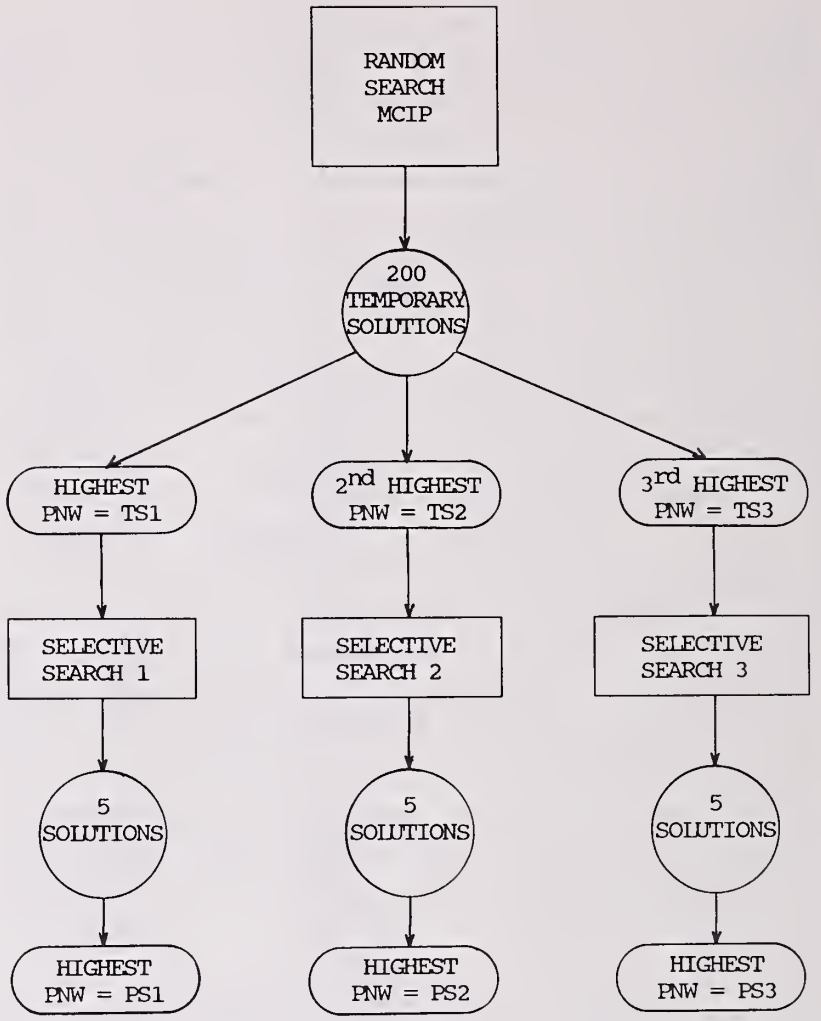


Figure 2.--Relationship between random and selective searches in establishing area-based plans.

Step Three: Integrating the Area-Based Plan With the Long-Term Strata-Based Plan

The three area-based plans identified above are then incorporated into 15-decade linear programs. These integrated plans are labelled ILP1, ILP2, and ILP3. Using the FORPLAN model, each area-based plan is treated as a coordinated allocation choice (CAC) that was selected from the zone containing the harvest units. The CAC contains all the hectares of the analysis areas that are within the harvest units selected for cutting. When implemented, the CAC forces a cutting schedule for the existing stands on each respective analysis area. It is important to note that the timing choices of the regenerated stands that result are not restricted by this method. The implication of this is that while this spatially feasible pattern occurs now, it does not necessarily repeat itself in subsequent rotations.

Other than forcing a particular set of AA's and road costs into the first three periods, these integrated linear programs (ILP's) are typical strata-based models. The objective function is to maximize PNW subject to an even flow of timber, nondeclining net revenues, and a perpetual timber harvest constraint.

For the purposes of comparing the three integrated plans, it is desirable to have a uniform flow of both volume and net revenue during periods 4 through 15. Volumes are allowed to fluctuate slightly (1-2%) from period to period, while net revenue is not allowed to decline. This provides enough flexibility to spread harvesting of the low valued stands throughout the planning horizon. Since the first three periods are fixed, the problem is reduced to finding a uniform cash flow over the last 12 periods, subject to minor volume changes.

[2]The use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of a service or product by the U.S. Department of Agriculture to the exclusion of others that may be suitable.

Discussion

The procedures outlined here provide a linkage between area-based and strata-based planning. It allows us to overcome the problems associated with each of these approaches. Spatially feasible plans can be generated and their long-term implications on volume and revenues can be assessed. While Monte-Carlo integer programming cannot guarantee an "optimal" solution to the standard mixed integer programming problem encountered in area-based planning, it is capable of quickly generating numerous high valued alternatives. This represents a considerable improvement over traditional methods where arriving at one or two feasible alternatives is a difficult task. When incorporated into FORPLAN formulations, the long-term effects of the MCIP solutions can be assessed, thus reducing the potential for disruptions in future harvest levels resulting from a myopic selection of harvest units.

The MCIP technique is advantageous in that it can quickly identify alternative harvest patterns should our assumptions change over time. It allows us to proceed with our immediate plan (period 1), knowing that flexibility exists in the selection of harvest units in subsequent decades.

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GIS PIP: The Role of the Geographic Information System In the Plan Implementation Process

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Abstract.--This paper describes the role of a GIS in the plan implementation process. The approach taken is to take an optimistic look at each phase of plan implementation and answer the following question: How can a GIS be used at this stage?

Integrated Resource Management (IRM) is defined as a land management philosophy which recognizes that all natural resources are connected through an intricate series of interrelationships. In order to recognize these interrelationships when a Plan is implemented on the ground, our Region has adopted a 13-step process which is called IRM. The 13 steps are:

1. Review Forest Plan
2. Develop Project Concept
3. Conduct Extensive Reconnaissance
4. Prepare Feasibility Report
5. Update Forest 10-Year Implementation Schedule
6. Conduct Intensive Reconnaissance, Survey, or Design
7. Generate and Compare Alternatives
8. Alternative Selection
9. Prepare NEPA Documentation
10. Create Project Record
11. Prepare Project Action Plan
12. Field Implementation
13. Monitoring and Evaluation

There is another process in our Region which has the initials IRM (Information Resources Management). When used in the context of information systems management, IRM refers to the process of managing our information resources--i.e.,

1. Information Systems Management
2. Data Processing
3. Data Analysis
4. Information Output
5. Information Use.

A GIS uses the five subsystems of Information Resources Management with data that is spatially locatable. In other words, in a GIS, a locational identifier associated with each item of data indicates where on the surface of the earth the information is located.

In order to facilitate the collection, processing, and display of data in an integrated resource environment, our Region is promoting the use of Geographic Information Systems (GIS) whenever the benefits of GIS are greater than the costs. This manuscript describes the benefits of using a GIS at each phase of Integrated Resource Management. (Henceforth, in this paper, "IRM" will mean "Integrated Resources Management".)

Phase 0--Pre-IRM GIS Work

Often the high front end costs of establishing a GIS can not be justified by its application to an individual project. The initial acquisition of hardware, software, and data is a time consuming and expensive undertaking which should not be underestimated. However, once a GIS is in place, the cost per project may be less than or equal to the comparative cost of a similar IRM process done manually. Also, the quality of the analysis and the project should improve and the likelihood of successful appeals should decrease with the availability of better information in the IRM process.

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The remainder of this paper describes how a GIS can be used in the plan implementation process. However, before a Forest can capture these benefits tomorrow, the following investment in GIS must be made today:

1. The Forest must decide to use GIS.
2. The Forest must budget for GIS. This includes the cost of hardware, software, data entry, data acquisition, and personnel. (At least one individual on the Forest will need to be designated as a GIS coordinator.) Beginning in FY 1988 the Regional Office budget includes recognition of GIS needs. The Forests need to make certain that these costs are incorporated into their Plan Implementation Schedules, as well.
3. Develop knowledge and experience with GIS through training and "hands on" experience in developing your Forest's GIS.

Once these three steps have been completed a Forest is in the position of being able to benefit from using GIS PIP (a GIS in the Plan Implementation Process). The remainder of this paper assumes that a Forest is ready to go with GIS PIP.

Phase 1--Review Forest Plan

A GIS provides us with another way of reviewing the Forest Plan. In map form, it provides the user with a description of the existing condition of the forest, as well as a vision of the forest of the future.

Mechanically, this is accomplished by overlaying the study area boundary with each relevant resource layer that is currently in the GIS. Products produced by the GIS at this stage include graphic output in the form of maps, and acreage summaries.

When reviewing the plan, we should first view the overall landscape. A GIS can allow us to visualize a complete picture of the spatial composition of vegetation, and the general location of facilities, roads, trail locations, culturally and environmentally sensitive areas, land ownership and use patterns, and other basic resource information in the project area.

This information can be used to evaluate locations for projects to be implemented. A part of Phase 1 is determining what Plan direction is applicable to the project area. A GIS can include narrative information such as standards and guidelines. In other words, if a location is known, a query can indicate what standards and guidelines apply to that area.

If standards and guidelines are not in the GIS, the GIS can still help to locate the standards and guidelines in the Plan. This can be accomplished by querying the GIS for an inventory of resources in the project area. Many standards and guidelines are tied directly to the characteristics of the land. For example, if the GIS indicates that the project area is in mixed conifer under 40% slope, the standards and guidelines in the Plan may indicate that we must that we must manage for the hairy woodpecker, elk, red squirrel, and turkey.

Alternatively, a GIS can help us to locate more specifically where a project should be implemented. For example, let's assume that an activity must take place where a specific combination of soil, slope, and vegetation occur. The GIS could be asked to display all occurrences of this combination of conditions. If alternative locations exist, the GIS could be used to select the best location for a more detailed analysis later on in the IRM process. In the later phase of IRM, the GIS could be used to "zoom in" on the best location with more site specific analysis at the project level.

This phase of IRM marks the beginning of project scoping (NEPA definition). By displaying the characteristics of the project area in tabular and map form, the GIS will provide resource specialists with information that will indicate potential ICOs. It can be used to indicate if this location has unique resource opportunities that are of interest to the public or are of interest to a specific management concern.

For example, a part of our land ethic and a part of our plan indicates that we are going to obliterate so many miles of unneeded roads. The GIS can be used to indicate if an opportunity for this activity exists in the project area. A part of Phase 1 of IRM in the Citizen Participation PIP is maintaining forest LMP contacts. If there is a citizen group that is interested in this topic, we can indicate that the road density will be reduced from some figure "X" to some figure "Y" in the project area. Or a GIS could be used to display exactly which roads in what locations could be closed. A map display might be more relevant to citizen participants if it can be comprehended more easily than numerical data. Also, many issues and concerns deal with the spatial aspects of plan implementation and not with statistical averages. That is, whether or not a specific road from point "A" to point "B" will be closed is more of an issue than whether or not the road density will change from "X" to "Y". A GIS is an excellent communications medium for public involvement.

The GIS can be used to define the influence area of the project considering potentials for direct, indirect, and cumulative environmental effects. For example, a display of the location of all projects underway and in the 10-year plan implementation schedule will provide an early warning of potential cumulative effects.

This illustration will facilitate developing a consistent set of projects. For example, the display of a developed recreation construction project without a road or visa versa would indicate a lack of coordination that would need to be remedied.

Phase 2--Develop Project Concept

The purpose of Phase 2 is to determine precisely what this project will be designed to do and why. The data and maps produced by the GIS in Phase 1 will be used in Phase 2 to develop the site specific Icos and objectives for the project(s).

The identification of site specific ICOs may lead to the identification of additional themes that are required in the GIS. These may either be new resource layers that are not contained

in the standard regional and Forest-specific resource layers, or existing layers which require more site specific detail for project analysis. If additional automated map information is needed, its acquisition or preparation must begin now, prior to its use later on in the IRM process.

When data requirements for a specified project are defined they must be based on the ICOs. The only information needed is what is required by the decision maker to address the decision that needs to be made.

The BLM (Webster 1987) uses a process called "cartographic modeling" which is a useful means for defining what information is needed by a decision maker. Cartographic modeling provides a conceptual framework for defining what information is needed.

For example, let's assume that the Plan says that a hiking trail will be constructed in the project area. What information is needed to formulate and evaluate alternatives?

The conceptual framework could be structured as follows:

THE QUESTION	CRITERIA	FACTORS	RESOURCE LAYER
Which corridor is most suitable for a hiking trail?	1. Erosion Hazard	Soil Properties, Vegetation, Slope Steepness & Complexity	Multilevel TES (Terrestrial Ecosystem Survey)
			DEM (Digital Elevation Model)
	2. Hiking Difficulty	Soil Properties, Vegetation, Slope Steepness & Complexity	Multilevel TES
			DEM
	3. Visual Quality	Views, Attractiveness	VQO
			Variety Class
			Distance Zone
	4. Recreation Opportunities	Recreation Attractiveness, Physical Setting	CR Maps: Historic, Prehistoric, Arch. Sites
			ROS Class
		Noise	Dispersed User Density
			Facilities
			Transportation
		Water Quality, Supply	Potable Water
			Water Bodies
	5. Cost	Soil, Vegetation, Slope, Erosion Hazard	Multilevel TES

Note: As the above cartographic model indicates, some resource layers such as the Multilevel TES Map have multiple uses within a GIS analysis. Also, just because a needed layer of information is defined, this does not mean that we have to go out and digitize a new map. Often, the recommendation or manipulation of existing data can give us the desired information. For example, a distance zone layer was desired to evaluate visual quality. However, instead of digitizing a new map with foreground, midground, and background indices, it may be possible to get the required information by running a viewshed analysis subroutine using the DEM (Digital Elevation Model) data that is already in the GIS. Similarly, if a map of fragile soils was desired and didn't exist, it might be developed by analyzing information already contained in the TES (Terrestrial Ecosystem Survey), DEM (for slopes and elevation information), and recent fire area maps.

Phase 3--Conduct Extensive Reconnaissance

The purpose of this phase is to determine by means of a brief field trip, if the project concept developed in Phase 2 will work. The GIS is involved with this phase in several ways.

First, as indicated in the discussion of Phase 1, the GIS can indicate where on the ground Phase 3 should take place. Field time can be saved as ID Team members visit only those areas that have been pinpointed by the earlier analysis with the GIS.

Second, tabular data, statistical analyses, maps of individual layers, and overlaid maps developed by the GIS provide tools that are useful prior to, during, and after extensive reconnaissance.

Third, several products of extensive reconnaissance have a direct tie to the GIS. These include the following:

a. Map or maps of project planning area showing known resource information.

b. Statistical reports on data in project planning area.

Phase 4--Prepare Feasibility Report

In this phase a Project Feasibility Report (PFR) is prepared. The PFR demonstrates whether or not the project is both technically feasible and economically feasible. The line officer makes a decision based on the report to proceed or not to proceed.

The project initiators either prepare the PFR or, at a minimum, provide information to the line officer concerning the project's feasibility. GIS information developed in the earlier phases will be one source of useful information.

GIS data related to technical feasibility might include the location of cultural resources, location of wildlife habitat and riparian vegetation, inventory of sensitive soils, VQO objectives, etc. The GIS could indicate how a variety of technical feasibility factors interrelate with each other through the devel-

opment of map overlays and other cartographic modeling techniques.

GIS data can contribute to the analysis of economic feasibility as well. For example, road costs are related to the status of existing roads, distance from sources of aggregates, location of sensitive resource areas, existing soil types, and slope conditions. Linkages with resource data components of the GIS such as the stand data base can indicate information on the benefits to be derived from the resources in the project area. For example, stand data would indicate the volume that is available for harvest--i.e., timber benefits.

GIS products from this phase that would be included in the PFR are:

a. Maps delineating
   i. the above items,
   ii. proposed location of resource project area,
   iii. pertinent known information within and adjacent to the project area, and
b. data indicating potential outputs and impacts.

Phase 5--Update Forest Plan 10-Year Implementation Schedule

The main objective of this phase is to update the Forest's 10-Year Plan Implementation Schedule which is maintained on a spreadsheet. The purpose of the spreadsheet is to assure that projects are scheduled in a sequence over time that works toward the desired future condition of the Forest.

Another achievement of Integrated Resource Management is that projects be identified together in an integrated manner within the same area of land. The GIS can be used to illustrate the group of projects for a specific, contiguous area of land needed to achieve the desired future condition. The pattern of implementation over space must be integrated with the pattern of implementation over time. This provides the user with a description of the existing condition of the forest, as well as a vision of the forest of the future. This will enable subsequent project initiators on this and related projects to see where they fit into the big picture.

Phase 6--Conduct Intensive Reconnaissance, Survey, or Design

The objective of this phase is to acquire all of the specific on-the-ground knowledge of the project planning area and its resources necessary to design a project that fully addresses the ICOs, sale objectives, and appropriate resource objectives. All site specific information needed for the project environmental analysis is collected during this phase (e.g., road location, cultural resource survey, T&E survey, fence location, etc.).

Products of this phase include more site specific data which is entered into the GIS. For example, if a timber sale is proposed within the project area, the boundaries of cutting units can be digitized and more precise data by cutting unit can be defined. This clarifies within the GIS the specific situation involved in this project analysis.

Phase 7--Alternative Generation and Comparison

The objective of this phase is to develop a reasonable range of alternatives including a "No Action" alternative. At this stage, a GIS with a variety of cartographic modeling procedures can be used.

One approach is the computer overlay mapping technique which is an automated version of the old plastic overlay approach which was popularized by Ian McHarg. By assigning different weights to different resource layers according to the objectives of the alternative, an alternative spatial pattern can be developed for the project area.

The overlay approach allows various resource layers to be integrated into a new map which displays resource interactions in the project area. For example, overlaying a road map on top of a map of critical wildlife habitat will illustrate areas of possible conflict between transportation development and wildlife protection.

A new layer could be generated for each alternative that is formulated. For example, one layer could indicate which specific cutting units would be treated if an alternative for a timber sale were adopted. Once this new layer is digitized, it could be used in conjunction with existing layers in future analyses.

Other GIS techniques can be used in the analysis and development of alternatives. One such example is the creation of buffer zones. A buffer zone is an area within a specified distance from a particular feature on a map. For example, a buffer zone around a proposed road may be used to define the area of wildlife habitat that may be potentially impacted by the road. Acreage summaries of affected areas, as well as mapped information, can be produced by the GIS.

Another example of a useful GIS technique is something called "viewshed analysis." A viewshed map can indicate if resource development (a mining operation, timber clearcut, etc.) is within the view of a proposed campground.

In addition to a variety of GIS techniques, other approaches to formulating and evaluating alternatives are available. Pure subjective judgment and experience can be utilized to generate alternatives if desired. Or, if desired, more automated approaches (ranging from project analysis spreadsheets to network analysis models) may be employed. However the alternatives are formulated, they may be depicted in map form and evaluated (for example, acreage and output summaries) using the GIS. The comparison of alternatives may be based, in part, on the output of the GIS.

GIS products from this phase could include map output for each alternative, as well as displays and tabular summaries of the resource attributes of each alternative.

Phase 8--Alternative Selection

In this phase, a proposed action is selected by the appropriate line officer. The line officer may include instructions to modify or refine any or all of the previously conducted analysis, which will require recycling back to previously conducted phases.

Phase 9--NEPA Documentation

The purpose of this phase is to complete environmental documentation. Products of this phase may include environmental documents (such as EA, FONSI, DN, EIS, ROD) and/or a categorical exclusion. These NEPA documents can incorporate maps and data produced by the GIS for a documentation of the input data and rationale for developing alternatives, as well as a description of the effects of alternatives.

Phase 10--Create a Project Record

The purpose of this phase is to have all pertinent information concerning the project in a single collection packet at one location for easy access. With a GIS this would include all relevant hardcopy output and any necessary references to data residing within the GIS data base or procedures used to manipulate the data for the analysis of this project. Material, relevant computer files need to be archived if this is cheaper than the expected cost of regenerating them at a later date. The availability of an on-line GIS system for answering some of the queries from the public during the citizen involvement process gives the forest a real-time project information system in addition to a static set of project records which are available on the shelf. Phase 10 captures the results of the previous phases in automated form. This may require more digitizing and data entry.

Phase 11--Prepare Project Action Plan

The objective of this phase is to specify who does what, when, where, and how the project is implemented on the ground. Products of this phase include final maps, layouts, surveys, designs, etc. Although alternative mapping techniques (such as the Autocad software which is currently employed by engineers in our Region) can be used, the GIS may be applicable in this phase as well.

Phase 12--Field Implementation

The purpose of this phase is to accomplish the project in accord with the final decision. This is the move from the paper product (produced in part by the GIS) to the ground. It is conceivable that a reference to the paper product will be necessary during this phase.

Phase 13--Monitoring and Evaluation

The objective of this phase is to monitor implementation and completion of the project and to evaluate the success or failure of project design.

The GIS will prove useful in a future evaluation of the project by tiering treatments to the ground. It should be relatively easy to locate projects and evaluate whether or not the treatment met the long term objectives and goals for the area. For example, this will give us a data base to say that, on a given land type or habitat type, such and such a mitigation measure worked (or didn't work).

While the project is being implemented and afterwards, it may be necessary to update the GIS data base. For example, a project design may be adjusted when on-the-ground conditions warrant (e.g., finding a previously unknown spotted owl territory or cultural resource site). Products of this phase will include an updated GIS as well as a project monitoring report.

Concluding Thoughts

As described in this paper, GIS can be used successfully during each phase of Integrated Resource Management (IRM). IRM is defined as a land management philosophy which recognizes that all natural resources are connected through an intricate series of interrelationships.

These interrelationships are complex and are not always well understood. The purpose of GIS is to help us comprehend these interrelationships. To maximize the utility of GIS, we must understand the interrelationships between GIS and IRM.

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Modification of an Initial Attack Simulation Model to Include Stochastic Components

Jeremy S. Fried and J. Keith Gilless[1]

Abstract.--The California Fire Economics Simulator-Initial Attack Module (CFES-IAM) is an MS-DOS micro-computer based planning tool developed for the California Department of Forestry and Fire Protection (CDF). CFES-IAM version 1, now in use, is a deterministic simulator which models initial attack on a limited number of representative wildland fires using data that describes an "average" fire season. Modification to better reflect real-world variability in wildfire occurrence, behavior, and initial attack control efforts is now in progress. CFES-IAM version 2, now under development, will be a clock-driven, next-event simulator. It will draw many of the key parameters describing simulated fires (e.g., time of day, fire rate of spread, and fireline production rates) from stochastic distributions. The parameters of these distributions are now being estimated for each CDF planning unit using local data. CFES-IAM version 2 will calculate expected values and confidence intervals for annual fire losses and control costs on a planning unit using the results from repeated simulations.

The occurrence of wildfires, the physical behavior of these fires, and the effectiveness of initial attack efforts to control them are all phenomena characterized by considerable uncertainty. Most prior applications of stochastic simulation to these problems have been rather narrowly focused (Martel 1982). Attempts at an integrated stochastic representation of these phenomena have never advanced to widespread implementation for a variety of computational, budgetary, and administrative reasons (Bratten et al. 1981, Mills and Bratten 1982).

The California Fire Economics Simulator-Initial Attack Module (CFES-IAM) is an MS-DOS micro-computer based planning tool developed by the authors for the California Department of Forestry and Fire Protection (CDF) (Fried and Gilless 1988). CFES-IAM version 1 is based upon the same deterministic simulation concepts as the U.S. Forest Service's Initial Action Assessment model (U.S. Department of Agriculture, Forest Service 1985). While CFES-IAM version 1 has been well received within the CDF, the limitations of its conceptual framework have already motivated efforts to develop a new version of the simulator that reflects real-world variability in wildfire occurrence, behavior, and initial attack control efforts.

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CFES-IAM version 2 will be a clock-driven, next-event simulator. It will draw many of the key parameters describing simulated fires (e.g., time of day, fire rate of spread, and fireline production rates) from stochastic distributions. The parameters of these distributions are now being estimated for each CDF planning unit using local historical fire records. Version 2 will calculate expected values and confidence intervals for annual fire losses and control costs on a planning unit using the results from repeated simulations, providing critical data for the CDF to evaluate its organization's ability to respond to both moderate and extreme fire seasons. This paper documents the ongoing modification of CFES-IAM version 1 to reflect the stochastic character of wildfire occurrence, behavior, and initial attack control efforts.

Fire Occurrence Module

Multiple fire starts are a major problem for the CDF. To permit realistic simulation of this phenomenon, CFES-IAM version 2 will necessarily be a next-event, clock-driven simulator. After processing an event (e.g., fire ignition, arrival of a fire-fighting resource, or fire containment), the simulator's "clock" will advance to the next event, explicitly recognizing the importance of chronological and spatial proximity. Further-

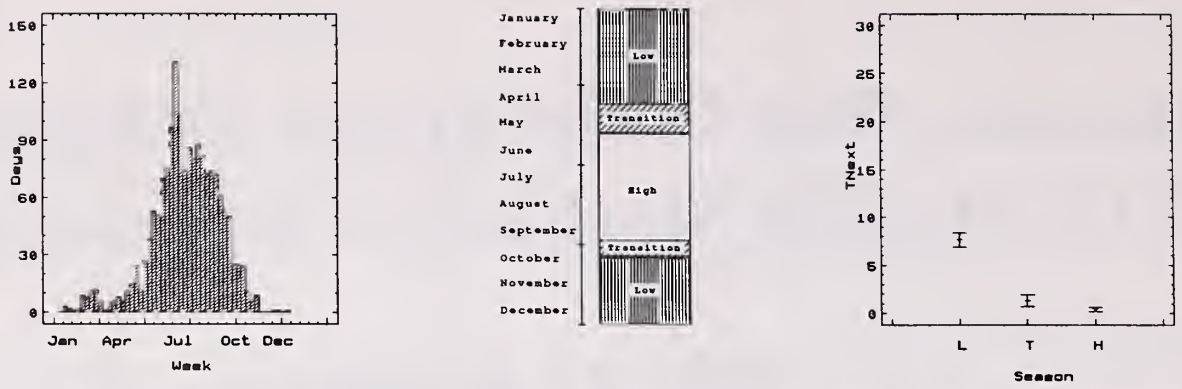


Figure 1.--(a) Number of fires per week over 5 years. (b) Low, Transition, and High fire seasons. (c) Ninety-five percent confidence interval plots of TNext, by fire. (All data are from historical fire records for the Nevada-Yuba-Placer ranger unit, California Department of Forestry and Fire Protection.)

more, it is important that version 2 be able to generate fire starts in patterns that are consistent with an area's fire history.

Four evaluation criteria determined the nature of CFES-IAM version 2's fire occurrence module. Close correspondence was sought between generated sequences of fires and historical fire records with respect to:

1. Distribution of the number of fires per year.
2. Distribution of fires by time of day.
3. Frequency and severity of multiple fire days (days with more than one fire).
4. Distribution of fires by season (or time of year).

Correspondence between the historical and generated distributions of number of fires per year is important for capturing the scale of the fire management problem. Agreement between historical and generated distributions for time of day is critical for simulating initial attack on multiple fire days, and to reflect the fact that some firefighting resources can only be used during daylight hours. Correspondence between historical and generated sequences of fires with respect to the frequency and severity of multiple fire days is necessary to evaluate the ability of the CDF to deal with severe fire seasons (i.e., those characterized by longer response times and decreased response capability). Finally, a match between historical and generated fire sequences with respect to the distribution of fires by season (or time of year) is important given seasonal differences in fire organizations' staffing and response capabilities.

Before finalizing the model structure, we analyzed CDF databases containing the date and time of occurrence, location and size at arrival and upon control for each wildland fire since 1981 in three ranger units located in the western foothills of the Sierra Nevada and on the eastern margin of the San Joaquin Valley. Altogether, these databases contained information on 4,000 fires. Distributions developed for the Nevada-Yuba-Placer (NEU) ranger unit are presented here to illustrate the structure of the occurrence module.

Most next-event, clock-driven simulators are based upon a single distribution describing the time between events. This approach was rejected because when used to simulate wildland fires in California, the resulting distribution of fire occurrence by time of day failed to demonstrate the diurnal pattern characteristic of real fires. The short duration of most fires fought by the CDF pointed to an alternative approach, one in which fire ignitions for any day are generated independently of those for preceding or subsequent days. This method requires the estimation of not one, but three distributions, which together can generate a sequence of fire ignitions over the course of a day.

California's annual pattern of fire occurrence suggested the division of the calendar year into three seasonal classes of relatively homogeneous fire frequency, referred to here as the Low, Transition, and High fire seasons. Inspection of histograms of the number of fires per week (fig. 1a) and Tukey multiple range tests of the time between fires (TNext) by week helped to determine these divisions (fig. 1b). The Transition season typically included 3 to 5 weeks in the spring and another few weeks in the fall when fire incidence was higher than in the Low season but less than in the High season. For all three ranger units, mean TNext was significantly different for each season as shown by Means/95 % confidence interval plots (fig. 1c).

The distributions that best described the probability of occurrence (Fireday), number of fires per day (Multiplicity), and time of day (Tod) of the fires were identified for each season. Fireday, defined to be 0 for days on which no fires occurred and 1 otherwise, was easily characterized by a Bernoulli distribution for each season. Histograms showing the relative frequency of Multiplicity by season, for days on which fire(s) occurred, led to the conclusion that a geometric distribution best described the transform (Multiplicity-1) (fig. 2). Although the degree of Multiplicity represented in the Low and Transition seasons was sometimes insufficient to calculate chi-squared statistics, the fit of these geometric distributions over all seasons combined was acceptable, and far better than any logical alternatives such as the exponential distribution.

Unlike Fireday and Multiplicity, Tod exhibited no seasonal differences. Thus, a single Tod distribution was estimated. Frequency distributions of Tod varied in appearance, but all had central tendencies when left-shifted 5 hours (so that 0 corresponded to 5 a.m. and 23 to 4 a.m. the next day). Some ranger units' Tod distributions exhibited a broad peak between 11 a.m.

and 7 p.m., and were best fit by beta distributions normalized to a 0-1 scale. Others, like the NEU ranger unit's Tod distribution, had high, narrow frequency peaks from 12 p.m. to 4 p.m., and were best fit by Poisson distributions (fig. 3).

Experimentation with this module has shown that it generates sequences of fires with TNext patterns quite similar to those of historical fires. The central tendency and variability of the total number of fires in these generated sequences compare favorably to their historical counterparts.

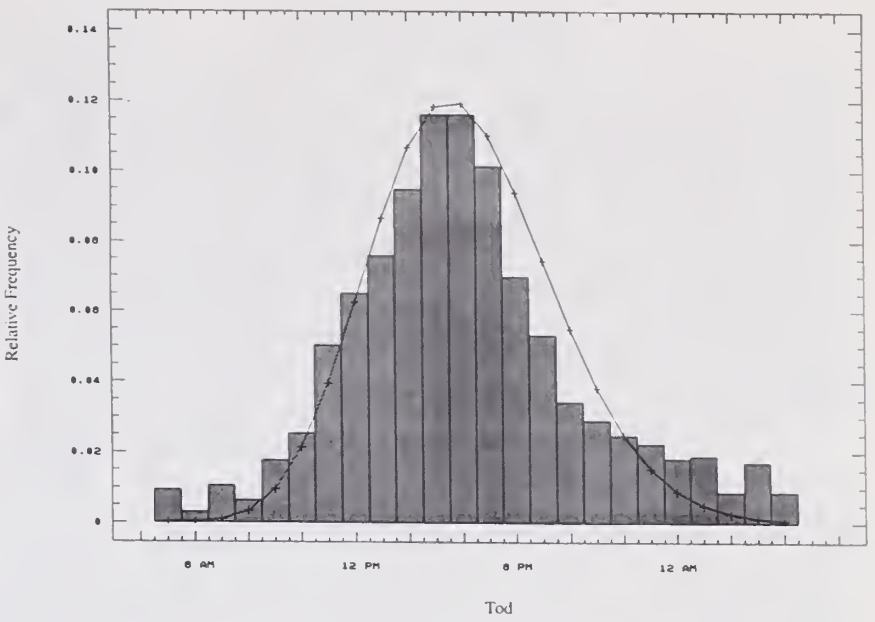


Figure 3.--Poisson Time of day (Tod) distribution fitted to historical fire records for the Nevada-Yuba-Placer ranger unit, California Department of Forestry and Fire Protection.

Attack Module

The sensitivity of CFES-IAM version 1 to variations in dispatch and firefighting productivity prompted the development of a stochastic attack module to represent these phenomena in version 2. For a simulated fire, the attack module generates initial attack strategy (i.e., head, flank, or indirect attack), tactics for firefighting resources capable of more than one kind of line production (e.g., mobile attack, hoselay, or handline for engines), and sustainable line production rates for firefighting resources, contingent upon the location, time, spread rate, buildup time, and dispatch level that define the fire. The attack module does not address variability in dispatch due to such factors as multiple fires, time of day, and fire danger as they are implicitly treated by the occurrence module.

Unfortunately, the fire literature provided no guidance for selecting strategies or tactics, and no information on production rates beyond tables of average rates by fuel and resource type. These tables, which are often based on only one observation per cell, provided insufficient information to serve as the basis for any kind of stochastic treatment. Ideally, we would like to directly measure the production rates of many firefighting resources on many fires and fuel types; unfortunately, past efforts of this type have been less than unqualified successes, largely due to the insurmountable logistical problems in deploying non-firefighting observers to measure ongoing line construction activity. Diligent researchers commanding small armies of earnest student observers spread throughout the state have been lucky to record 100 observations of line construction in a year, spread over 12 to 15 firefighting resource types, 5 to 8 fuel types, and 5 slope classes. Rather than launch another such (doomed) attempt, we opted to tap the knowledge of the experienced firefighting professionals who directly supervise the construction of fireline and make daily judgments about productivity when deploying firefighting resources at initial attack fires. The most practical way of accomplishing this was to survey fire engine captains, handcrew bosses, and dozer operators to solicit their expert assessments of site specific productivity for the types of firefighting resources that they command.

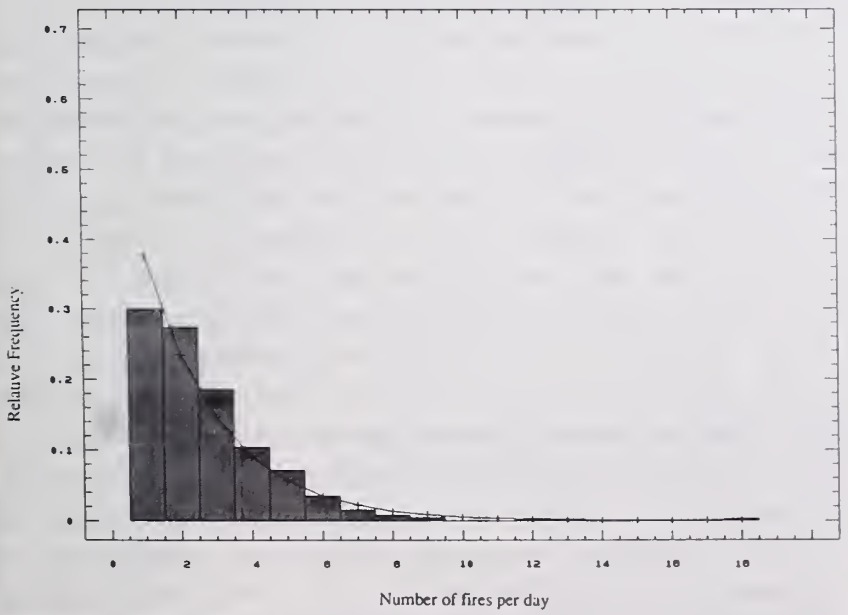


Figure 2.--Geometric Multiplicity distribution fitted to historical fire records for the Nevada-Yuba-Placer ranger unit, California Department of Forestry and Fire Protection.

Because strategies, tactics, and production rates can be affected by local conditions, such as lava dikes, ubiquitous fences, or topography, we elected to conduct the attack survey at the ranger unit/contract county level, relying on local firefighting professionals to provide this information for the areas they know best. The survey is administered via a form for each unique combination of fuel, slope, and habitation density (control condition) on a ranger unit, accompanied by photographs depicting the fuel and topography of a particular location representative of that control condition. For the two ranger units surveyed thus far, this required one or two forms for each of three or four fire management analysis zones (FMAZs).

Each form contains a section for entering the percentage of fires, by dispatch level, on which the respondent would employ a head, flank, or indirect attack. For engine captains, an additional section queries for the percentage of fires for which mobile attack, hoselay, or handline tactics would be used for each of these strategies. Survey estimates of the relative probabilities of the different strategies and tactics are averaged for each control condition and dispatch level on a planning unit.

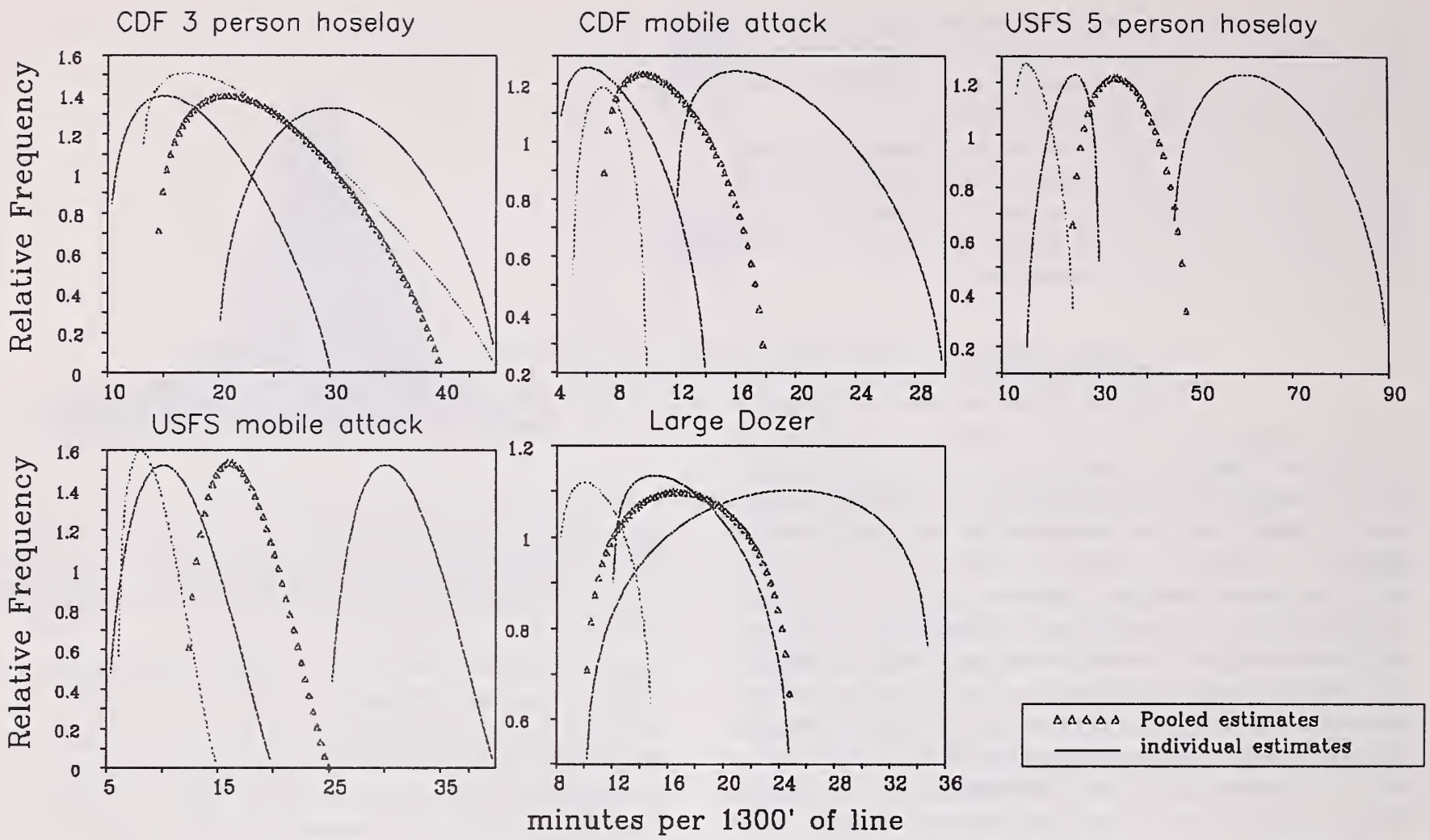


Figure 4.-- Beta distributions of the time required to complete 1,300 feet of fireline in grass fuels for five equipment/tactics combinations (distributions derived from individual estimates indicated by solid lines; from pooled estimates, by triangles).

Before deploying firefighting resources to a simulated fire, CFES-IAM version 2 will randomly select a firefighting strategy and engine tactic on the basis of these probabilities.

On a final section of the survey form, the firefighter enters information pertaining to the line production rate for the resource type that he or she supervises. This includes an estimate of the best possible, the most likely, and the worst possible production rates. These are defined as the rate when everything is functioning perfectly with fresh, motivated personnel, the rate one would expect to see most of the time and the rate on a day when everything seems to go wrong, respectively. In addition, participants are asked to estimate an increment such that 50% of the time actual production rates will fall in the range from "most likely - increment" to "most likely + increment." All production rates are estimated as the number of minutes to construct x feet of held fireline, where x depends on the fuel (500 feet for brush and coniferous timber, 1,300 feet for grass and oak woodland); thus, smaller numbers of minutes imply faster production rates. This question format was employed because firefighters rarely think in terms of production rates but *do* make daily judgments about the time required to complete a section of fireline.

We generated beta distributions of the number of minutes to construct a length of fireline from the best, most likely, and worst case estimates, adapting a technique originally developed for probabilistic PERT analysis. The estimates of the increment defining a 50% range were used as a check on the standard probabilistic PERT assumption that the standard deviation is one-sixth the range from the worst to the best time, and eventually to generate estimates of variance to be used in estimating the beta distributions. Distributions for different types of resources in grass (fig. 4) and brush (fig. 5) ranged from symmetric to highly skewed, and from narrowly concentrated to nearly uniform random. For example, hand crew bosses provided estimates that generated concentrated distributions, while USFS engine captains' responses for handline production by engine crews described distributions with virtually no peak (i.e., their estimate of increment such that the interval "most likely - increment" to "most likely + increment" spanned most of the range from best to worst time). Variances derived from individual estimates of production rate parameters were averaged for each resource type/control condition combination, increasing the similarity among distributions within each. The individual estimates were averaged for each combination to estimate pooled distributions for use in CFES-IAM version 2. Where there is little overlap among distributions based on individual estimates, (e.g., the USFS 5 person hoselay in grass, fig. 4), it may be preferable to also include data from adjacent

ranger units to arrive at a more robust pooled distribution. It is interesting to note that the pooled (and most individual) distributions are either symmetric or skewed towards faster production rates (i.e., fewer minutes to complete the fixed distance), indicating the respondents' belief that firefighting forces usually perform closer to their best than to their worst, a result consistent with the probabilistic PERT literature. This skewness suggests that accurate estimation of a symmetric increment may be impossible, and that a one-tailed estimate (e.g., what is the time to completion that you would expect to exceed only 1 out of 10 times?) may elicit better estimates of variance.

The data entry module of CFES-IAM version 2 will query for the production rate information from the survey. Upon executing a simulation, version 2 will calculate the beta distribution parameters for each resource type/control condition. A time, in minutes, will be stochastically generated from the appropriate beta distribution when each firefighting resource is dispatched, and the corresponding sustainable production rate for that resource will be calculated.

Fire Behavior Module

The most straightforward way to capture real-world variability in fire behavior in an initial attack simulation model is via a stochastic representation of forward rate of spread (ROS), since this single variable integrates both fuel and weather conditions. Together with a fire shape assumption (e.g., 2:1 ellipse), ROS determines a simulated fire's perimeter growth. This, along with the fireline production capability of the firefighting resources dispatched to the fire, can then be used to determine whether or not a simulated fire would be contained within specified simulation time and size limits.

Historical 2 p.m. "worst case" National Fire Danger Rating System ROS estimates are available for more than 200 AFFIRMS weather stations in California. Each fire record in the CDF's databases is now being augmented with the ROS estimate for the most representative weather station and fuel model. These ROS estimates permit preliminary estimation of ROS distributional parameters, by FDL and ranger unit. However,

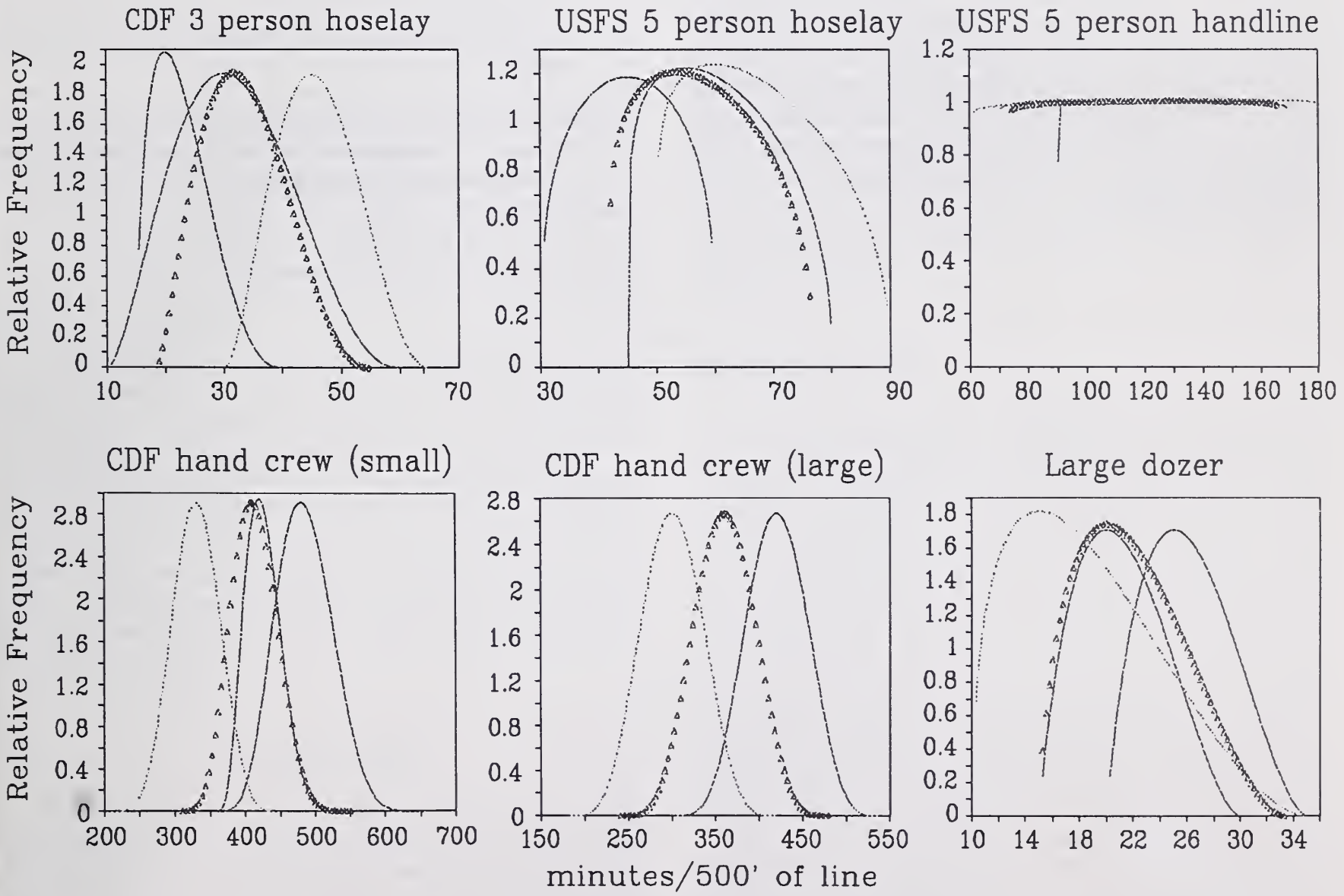


Figure 5.-- Beta distributions of the time required to complete 500 feet of fireline in brush fuels for six equipment/tactics combinations (distributions derived from individual estimates indicated by solid lines; from pooled estimates, by triangles).

final FMAZ specific parameter estimates will probably be derived from the set of all 2 p.m. ROS estimates from the representative weather station for days with a given FDL, thereby integrating additional years of available weather history. For simulation purposes, the characterization of a day in the fire season will be based upon either simple proportions or probit models. A separate study is now underway to assess the feasibility of adjusting 2 p.m. ROS estimates to reflect diurnal variation in fire behavior.

A potential weakness of this approach is that it would not reflect any correlation between fire multiplicity and variation in 2 p.m. ROS. We do not view this as a serious problem, since the strength of this correlation has not been established in the fire literature.

Conclusions

CFES-IAM version 2 will contain stochastic representations of wildfire occurrence, behavior, and initial attack control efforts. Estimation of the parameters of the distributions used to characterize these phenomena will be based upon ordinary local historical fire records. Experimental versions of the stochastic version 2 modules confirm the feasibility of micro-computer implementation of a more rigorous initial attack simulation model. Ultimately, providing local CDF decision-makers with a powerful analytical tool that they can master without extensive training may be of more value than the expected increases in the model's validity.

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Consideration of Risk in Forest Project Analyses

Eric L. Smith[1]

Abstract.--Risks are present in forest projects and should be considered in project analyses. Appropriate analysis techniques need to be matched to situations by considering physical and institutional factors. Various techniques have been applied to forest projects, but often only as research examples. Project planners need to not only measure risk, but also try to reduce or manage it.

Forest managers face uncertainty from many sources. When planning forest management projects and programs, these uncertainties must be considered to make choices among alternatives and to predict future forest outputs. The major sources of uncertainty are: (1) lack of information about resources and natural processes; (2) unpredictable changes in future demand for forest products; and (3) catastrophic natural events which can both damage resources and alter the natural environment. For the purposes of this discussion, I will define risk as being the variability which uncertainties cause in the desired forest management outputs.

Within the fields of operations research, business management, and economics, many analytical procedures have been developed to incorporate consideration of risk in decision making analyses. Many of these procedures are widely known to those conducting analyses of forest management projects, and there are many published examples of their application in forestry. However, procedures to calculate and consider risk in forest management project analyses are not included in many cases where significant risk exists. Furthermore, risk analysis techniques are sometimes poorly suited to the applications to which they are applied.

Dimensions of Risk

There are a variety of risk analysis procedures and a variety of situations in which they may be applied. If the analysis is to be useful and appropriate, it must be matched to the context in which the decision is being made. There are three major dimensions which should be considered. First is the nature of the uncertainties being faced and the degree to which they can be measured and translated to risk in outputs. This can be labelled the statistical dimension of risk. Second is the size of the risk relative to the size of the project and to the size of the program of the administrative unit carrying out the project. This is an economic dimension. Third is the complexity of the decision being made--is the project being evaluated on a single criterion or on multiple criteria? This is a policy dimension, involving trading off risk and levels of different kinds of alternative outputs.

Statistical Dimension

The primary quantitative concept in risk analysis is probability. In classical statistics, a statement of probability is interpreted as the distribution of outcomes over repeated trials or the theoretical distribution of outcomes. The probability established by sampling or experimentation serves as an estimate of "true" probability. Many natural resource management situations are a result of natural phenomena over large areas and long times. Insect epidemics are an example of such a phenomenon. Often such a set of circumstances is present in which various factors are known to have an effect on the outcome, but no adequate model or experimental results are available to predict the aggregate outcome of these circumstances. In these cases, the statement of probability takes on a Bayesian meaning--it is a statement of belief in the distribution of outcomes.

The two extremes of the statistical dimension could be labelled "unique" and "repeatable" situations. The significance of this dimension is the source and properties of the predictors of outcomes. In repeatable situations, one can seek experimental or empirical results with which to make predictions. Past results or sampling will allow precision estimates to be attached to predictions.

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With unique situations, judgment and expertise, or "expert opinion," must be employed. Stochastic simulation models may also be useful, where outcome distributions are created based on probabilistic inputs. In using techniques such as decision analysis, elementary texts often advise employing "expert opinion" or perhaps the opinion of the "decision-maker" to provide probability estimates. Practitioners should be aware that psychological research in this area has shown that the quality of information obtained using this approach depends how the questions are asked (Fischoff 1984, Kahneman et al. 1982). Biases in estimates are likely without corrective procedures. Application of subjective assessments in forest protection models is discussed by Cleaves et al. (1987).

Economic Dimension

Those studying risk in the context of gambling have long known that the desirability of a bet varies both with the odds of winning as well as the size of the bet. It is the importance of the size of the bet, the amount at risk, which has introduced the concept of utility and risk preferences into risk analysis. A person who is willing to take a wager where the expected value of the payoff is equal to the amount wagered is defined as being risk neutral. However, an individual may be risk neutral when small amounts are involved, but risk averse (requiring an expected value greater than the amount bet) when larger amounts are involved. It has been stated by Arrow (1965) that a government should be risk neutral in its investment policy. This principle has been used to argue that public natural resource agencies should, in general, disregard the magnitude of risk in a decision and consider the expected value of the payoff.

Because the principle that marginal utility declines with increasing quantity can be applied to resource management, outputs at different levels can have different per unit value. Because many forest outputs do not have market values, establishing marginal values is difficult. In lieu of this approach, we can use the concept of risk adversity, particularly in the domain of losses, to substitute for establishing marginal values. A good example of such use would be for endangered species management. Here, a choice of two projects which could affect the population should probably be made on a risk-adverse basis, favoring the alternative with the least chance of a large loss. Risking an rare resource such as this is analogous to making a large wager and being wiped out on a single play.

The logic that risk adversity is an appropriate substitute for marginal valuation can be extended to other situations, to some extent. The larger the amount of assets which are involved, the more negative consequences are likely when losses occur. Catastrophic losses from fire or insects may cause regional economic impacts or negative river drainage impacts which would not be present with similar, but smaller, events.

The analyst must also be aware that the responsibility for making decisions for alternatives containing risk is likely shift up the organizational ladder as the resources at risk increase in value. If the relative magnitude of the risk is obscured by the analysis, the decision-maker may find himself or herself taking inappropriately large risks. There is an value of information aspect here as well. Large potential losses or large investments obviously merit more study, more data collection, and more carefully chosen analytical techniques. However, if similar small decisions are faced repeatedly, a fixed policy or specially designed heuristic decision process could be justified.

Policy Dimension

When more than one criterion is applied to a decision or when a project involves multiple objectives, a policy issue arises in how the criteria should be weighted. The simultaneous consideration of risk along with other variable creates a considerably complex analytical problem. Such situations are common in natural resource management, but are often approached in a way which ignores the complexity. Under such circumstances, it is usually the consideration of risk which is ignored. The use of linear programming for forest planning is a good example of this situation. Risk analyses involving tradeoffs between environmental health issues and costs often include both risk and multiple criteria consideration.

Just as the scale of the risk affects the level at which the decision is made, the multiple criteria situation calls for appropriate policy input. Techniques which rely on simple weighting schemes are not likely to capture the true preferences of the decision-maker when the criteria are applied to specific choices. Even worse are procedures which implicitly assume these tradeoffs. On the other hand, displaying too much information or too many choices can overwhelm the decision-maker. One partial solution to this situation is the use of stochastic dominance techniques (Buckley 1986). This approach winnows out clearly inferior alternatives and identifies the differences among those remaining. It has been used in evaluating spruce budworm management policies (Thompson et al. 1979).

Areas of Application

The dimensions of risk considerations outlined above include both the need to consider the nature of the problem and the institutional environment of the decision when selecting and applying an analytical technique. What follows are examples of applications of risk analysis for forestry projects and planning.

Variable Discount Rates

The use of variable discount rates to adjust for the riskiness of projects is a form of risk analysis when two or more economic returns are being compared. This approach is intuitively logical and follows common business practice, where the customers

who are considered most credit-worthy or who are borrowing for less risk-prone purposes pay lower interest rates. Foster (1979) gave a simple illustration of this approach in a forestry context. Chang (1980) commented that this approach would give biased results if one had a declining marginal utility for the income produced, and that a constant rate applied to the expected value of the utility of the outcomes was a better approach.

Reed (1984) showed mathematically that a time-independent constant probability of total forest destruction has the same effect on the optimal rotation length Faustmann formula results as adding that probability to the discount rate. When the probability of destruction changes over time, the results are also effected by the reestablishment costs.

This approach is not useful when considerations such as salvage values are included. These discussions do serve to emphasize the existence of risk, however. It does seem useful to define the risk inherent in forestry projects in terms of discount rates as a first step, given that many analyses neither adjust rates for risk nor consider anything but an optimistic outcome.

Hertz-Thomas Method

Using a variable discount rate to express risk can only adjust the average return on the investment, and can only be easily used when outcome probabilities are simply expressed. A method of more completely displaying the effect of uncertainty on returns has been developed by Hertz and Thomas (1983). The method uses computerized Monte Carlo simulation to construct a probability density function of financial returns. The use of such a simulation technique allows the simultaneous consideration of several stochastic variables. It also has the advantage of displaying the probabilities of the entire range of outcomes. This allows the decision-maker to use whatever risk criteria he deems appropriate in evaluating the risk. The method is similar to sensitivity analysis, but superior, since the simulation model can handle variations in conditions simultaneously, which is important when variables are correlated.

Recent applications in forestry include an analysis of risk of insect attack in plantation investments (Anderson et al. 1987), and a similar analysis of plantation investments which incorporated variable future prices, costs, and yields (Lothner et al. 1986). The former displayed outcomes as a cumulative probability distribution of internal rates of return, while the latter used relative frequencies of net present value.

Decision Trees

The classical approach to making decisions under risk is by the use of decision trees. This represents the decision process as a series of decisions and probabilistic states of nature, making decision choices based on maximizing the expected values of probability distributions. The basic weakness of the method is that it does not allow for the tradeoff to be made between maximizing expected value and decreasing risk. Also, the problems of accurately assessing subjective probabilities are critical here.

Several applications of decision trees have been made in forest protection. In fire management, they have been used for both wildfire situations (Seaver et al. 1983) and for prescribed fires (Cohan et al. 1984). It is particularly important in wildfire situations that some conscious decision be made as to the tradeoff between minimizing the expected total fire costs and reducing the potential for very large fires. Normal use of decision trees will not provide guidance on this tradeoff. Talerico et al. (1978) have demonstrated the use of decision trees in a pest management context.

Risk in Planning and Harvest Scheduling

The use of linear programming models for forest planning and harvest scheduling has made the incorporation of risk consideration in these activities difficult. Models such as FORPLAN, used in National Forest planning, are already large and costly to run without the added complexity that risk consideration would add. Nonetheless, it is recognized that uncertainty exists in forest productivity, future output values, and future costs. Allowance for risk of reduced outputs are sometimes made by decreasing production rates for timber stands, reflecting average rates of damage from fire, pests, or other factors.

The effects of uncertainty and variation on linear programming models for forest planning applications has been analyzed by other authors (Hof et al. 1988, Pickens and Dress 1988) and summarized elsewhere in these proceedings by Pickens and Hof. These studies show that even without the uncertainties of catastrophic evens, expected value production estimates of stochastic variables can result in biased and infeasible solutions.

The effect considering pest epidemics could have on National Forest plans has been shown by a study involving tussock moth outbreaks on two National Forests (Forest Pest Management 1984). This study estimated the reduction in net present value which is likely to occur due to periodic tussock moth outbreaks, and the efficiency of two different spray treatments. The study created a random series of outbreaks based on historic frequencies, and factored the damage into production rates within a FORPLAN model. It was shown that both spray programs would have positive returns.

The tussock moth study approach, while showing for one Forest an almost 30% decrease in the expected present net value when the probable damage was considered, underestimates likely losses. By creating an optimal harvest schedule given a sequence of moth outbreaks, the model can arrange harvests and treatments knowing when future outbreaks will occur. The real occurrence of outbreaks would certainly be different than the randomly generated one used in the simulation. Therefore, the true optimal solution would also be different. Since a different optimal solution for a different outbreak sequence would be

expected to yield, on average, a net present value the same as in the modeled solution, the modeled schedule would likely yield a lower net present value for the different outbreak sequence.

Hoganson and Rose (1986) applied their innovative harvest scheduling solution technique (1984) to determine the risk effects of price uncertainty on a harvest scheduling problem. They emphasized the differences in the first period decisions, showing which subset of the stands would be treated differently given different future prices. Their logic is that as prices change in the future, new harvest schedules will be constructed. It is only the near term decisions which need to be made without the benefit of knowing some future prices. A similar approach could be applied to supply uncertainties involving fires or pests.

Risk Reduction and Management

Measuring risk and making decisions while considering risk is not all that can be done. Risk can be reduced and managed. The first step is to recognize the amount and sources of risk. As discussed above, "experts" are not necessarily able to accurately judge the probability of events. In fact, they generally predict too narrow of a range of possible outcomes and are too confident of their predictions.

Some risk is caused by uncertainties which could be reduced with additional information. "Value of information" analyses are well known to those familiar with operations research, but they are rarely applied to forestry problems. Many kinds uncertainties exist which cannot be resolved by data gathering, however, and they must be dealt with in other ways. One possible approach is planned diversification. In business, one such approach is portfolio management. The idea is to take actions which have risks which are negatively correlated to each other, or at least independent of each other. This has been considered in forestry in the context of financial uncertainties, but not, to my knowledge, in the context of biological or technological uncertainties.

Finally, we need to view some uncertainties and the risks they cause as being inevitable, and view our projects and plans as being temporary and subject to change and modification. Projects which are flexible or sound under a range of future conditions have an unmeasured benefit when judged under a single set of assumptions about the future.

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Identifying Sort Yard Locations With Size Dependent Processing Costs

John Sessions, John J. Garland, and Gonzalo Paredes[1]

Abstract.--Sort yards placed at selected intermediate points between timber cutting sites and mills have the potential for increasing the value of logs or trees destined for processing into different products. A two-phase modeling procedure is presented for identifying the efficient placement of sort yards using computations much simpler than those in standard linear mixed-integer programming methods.

In forest operations, the decision of how to transport trees from the stump to the manufacturing destination must consider: cost and effort of transporting the logs or trees to roadside, the relative efficiency of bucking in the woods or on the landing, legal restrictions on log or tree transportation, distance to mills, and the prices paid for logs or trees at their final destinations. An important alternative to consider is the construction of sort yards.

Sort Yard Functions

Sort yards, wood yards, log storage yards, mill yards, satellite sort yards, and dryland sort yards describe the location and set of activities related to materials handling at intermediate points between the landing (used for yarding and loading) and the point where these materials enter the mill or where they are transshipped to other locations, e.g., dockside for export, sale to another purchaser, etc. Sort yards may be located adjacent to a mill or transshipment point, or they may be at a central point nearer the woods operation some distance from processing plants.

Typically sort yards perform a variety of vital functions for a forest products firm. The majority or all of the functions listed below are performed at sort yards:

- -- A facility to separate and aggregate materials according to species, grades, sizes, and user requirements.
- -- A facility to measure materials for transactions, e.g., scaling, weight measurement, for payment.
- -- A location to store and inventory materials.
- -- A facility to upgrade and remanufacture materials for users.
- -- A product showplace, e.g., a place for export or other purchasers to review materials.
- -- A conversion facility, e.g., logs, chunks into chips via a portable chipper, or chunks into shake bolts.
- -- A significant generator of debris and waste material.
- -- A transportation hub for truck/rail/water transshipment, e.g., to quickly free log trucks for return to woods operations.

A sort yard may be most analogous to warehouse activities of general manufacturing except the materials handled may be trees, logs, poles, chips, shake or shingle bolts, or even firewood.

Locating Sort Yards

Forest products firms can analyze their choices for sort yards by considering the costs of construction, processing costs, the increased value of products processed in a sort yard, and various costs in a transportation network. Ideally, firms would like to know which sort yards to build to accommodate various sources of timber supply. Analysis procedures should also identify which sources should bypass sort yards as well and move directly to mills or other end points.

Analysis procedures may include various techniques that treat the fixed investment of constructing the sort yard. Sessions

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and Paredes (1987) describe a two-phase modeling method that solves the sort yard location problem with a given processing cost for each sort yard.

Size-Dependent Processing Costs

The two-phase modeling approach is modified here to account for processing costs which vary as a function of piece size. Most materials handling techniques in sort yards are piece-by-piece operations. Handling larger pieces reduces the cost per unit volume of sort yard processing. More significantly, handling small pieces (logs) in a sort yard is costly and should only be undertaken if value increases exceed the processing costs.

Each sort yard might have its own processing cost function that varies by piece size, but often the materials handling equipment is similar so a processing cost function of the type shown in figure 1 might be expected (Garland 1983). A simplified version of this cost function is used in subsequent examples to illustrate solution procedures for sawlogs and pulpwood.

Proportions of Piece-Sizes

Each log size has a unique processing cost through a sort yard. For computational purposes, however, we categorize loads of trees or logs arriving at a sort yard as belonging to a "proportion." For example, one proportion might be 40% small, 30% medium, and 30% large logs. We might categorize wood arriving from each of 100 operations as belonging to one of 25 proportions. The various sources may have a mix of proportions that approach normal, exponential, uniform, or other distributions of piece sizes depending on timber characteristics.

As we will see, the size of the problem rapidly increases with the number of proportions to be considered. Although using more realistic sort yard processing costs accurately portrays the value difference of gains over costs, we will need to achieve a compromise.



Figure 1.--Sorting costs ($/cunit) by piece size (cubic feet).

Modeling and Solution Approach

The construction of sort yards can involve considerable investment. The decision to construct the sort yard must include the cost of construction and operation, the increased value of wood that is achieved through improved cutting and sorting of logs in a more controlled environment, the ability to allocate parts of trees to alternative destinations, and the transportation cost of the various products over the transportation network.

Because of the fixed investment in a sort yard, the problem structure results in a linear mixed-integer programming problem. Problems involving even a small number of alternative sort yard locations tax the computational capabilities of current mixed-integer programming algorithms. We shall demonstrate a two-phase procedure for solving the sort yard location problem which overcomes the computational complexities of conventional linear mixed-integer programming approaches.

The solution strategy exploits the network structure of the problem. Two related shortest-path subproblems can be easily identified: one dealing with the path *from* the point of potential sort yard locations *to* the final destinations, and the other with the path *from* the point of harvest *to* the potential sort yard locations. We will first solve the shortest-path problem from the potential sort yard locations to the final destinations, and then combine these results with the original problem to solve a mathematical problem that is much simpler than the original problem. We explain below how destinations are defined here.

In the first phase we solve for the shortest path from all possible sort yard locations to destinations. This is normally a value-maximization problem in which both costs and revenues are considered. Costs are associated with the transport operations. Revenues correspond to the different prices at which mills purchase each commodity. Since commodities are not homogeneous; we add a "super" destination node for each commodity type. The mills purchasing a commodity are then connected by an arc to the corresponding super destination node. The cost coefficient of these arcs equals the negative of the per-unit price the mill offers for the commodity. This phase can be readily solved as a linear programming problem without any integer variables, or as a shortest-path network problem using any of a number of algorithms summarized by Smith (1982).

The results from the first phase (minimum-cost or maximum-revenue paths) from candidate locations to destination nodes, and the discrete location variables (with their associated fixed costs) are included, in the network for unsorted commodities, as additional arcs. For each candidate location there is one additional arc to each super destination. The original problem is now reduced to a shortest-path problem from timber sources to super destinations, with fixed costs represented in some of its arcs.

For problems involving less than approximately 50 candidate locations, this second phase can be solved as a conventional linear mixed-integer mathematical programming problem, with the integer variables being the location options. For larger problems, the second phase can be solved using any of a

number of heuristic procedures. Steinberg (1970) has demonstrated that for the facilities location problem, heuristics have satisfactory accuracy and require less computation time than the branch-and-bound algorithm commonly used to solve the mixed-integer linear mathematical programming problem. In the examples that follow we chose to use the heuristic implemented by Sessions (1987) to solve the second phase because it includes the explicit identification of optimal transport routes. This heuristic is based upon a procedure developed by Cooper and Drebes (1967) using a shortest-path labeling algorithm similar to that developed by Dijkstra (1959). Regardless, however, of the method chosen for solving the second phase, the two-phase modeling procedure is much simpler to formulate and solve than the conventional mixed-integer linear programming approach, because it involves much fewer equations.

The two-phase modeling method can be extended to encompass processing of logs or trees at the stump or at roadside, increasing the number of products provided at the sort yard, adding flow constraints on the sort yards, and analyzing over multiple periods. Construction of roads to alternative standards can also be considered if the roads are on the periphery of the network.

Example

Assume that the road network is as shown in figure 2. Sources are at nodes 1, 2, 3, and 4, with volumes and proportions of pulpwood and sawtimber given in table 1. There are two mills. One mill is at node 7 and the other mill is at node 8. The mills will pay according to the schedule in table 2 for delivered wood. The cost of transporting mixed wood, pulpwood, and sawtimber is given in table 3. Further assume that a sort yard could be built at any node except nodes 7 or 8. The cost to build a sort yard at any node is given in table 4. The cost for processing wood in the sort yard is $6 per cunit for pulpwood and $2 per cunit for sawtimber. If mixed wood is delivered to a mill, the delivered mill price is the weighted value of the pulpwood and sawtimber prices, less the penalty given in table 2. The objective now is to decide whether sort yards should be built, where and over which routes wood should be transported, and to which mills it should be routed.

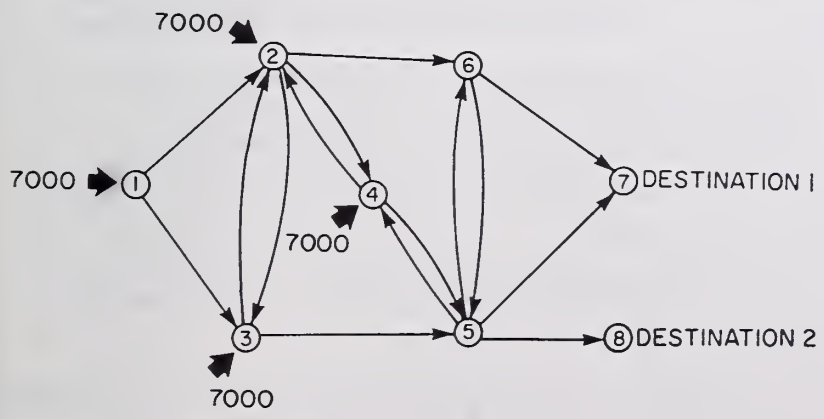


Figure 2.--Network showing four entry points and two destinations.

Table 1.--Wood sources and proportions of pulpwood and sawtimber.

Node	Volume *cunits*	Pulpwood %	Sawtimber %
1	7,000	30	70
2	7,000	50	50
3	7,000	30	70
4	7,000	50	50

Table 2.--Prices mills will pay for delivered wood.

Node	Pulpwood $/cunit	Sawtimber $/cunit	Mixed wood penalty $/cunit
7	40	100	5
8	50	90	5

Table 3.--Unit costs for wood transport for alternative products.

Link from	to	Mixed wood *$/cunit*	Pulpwood *$/cunit*	Sawtimber *$/cunit*
1	2	1.0	0.8	0.9
1	3	2.0	1.6	1.8
2	3	2.0	1.6	1.8
3	2	4.0	3.2	3.6
2	4	3.0	2.4	2.7
4	2	2.0	1.6	1.8
4	5	5.0	4.0	4.5
5	4	4.0	3.2	3.6
5	6	3.0	2.4	2.7
6	5	5.0	4.0	4.5
2	6	6.0	4.8	5.4
6	7	7.0	5.6	6.3
5	7	5.0	4.0	4.5
3	5	3.0	2.4	2.7
5	8	6.0	4.8	5.4

Table 4.--Initial investment required to build sort yard.

Location *(node)*	Initial investment *($)*
1	40,000
2	50,000
3	40,000
4	55,000
5	32,000
6	33,000

The problem is solved in two phases. In the first phase the shortest path (the one that yields the lowest transport cost for the sorted wood for pulpwood and sawtimber) is determined from each candidate sort yard location to the mill. The shortest path includes the choice of mill. This is done by linking the mill destinations together and adding a "super destination" at node 9 for pulpwood and another "super destination" at node 10 for sawtimber (fig. 3). The links joining the actual mills to the super destinations have a negative variable cost equal to the delivered prices the mills would pay for the respective products.

One unit of volume is now sent from each candidate sort yard location to each super destination, using the appropriate set of transport costs. In other words, the pulpwood transport costs are used when the wood is transported to the pulpwood super destination, and the sawtimber transport costs are used when wood is transported to the sawtimber super destination. The path that this volume takes will indicate which mill will be the destination (table 5).

Table 5.-- Shortest paths and costs for transportation of one unit of wood from each candidate sort yard node to the mill. Negative costs are transport costs minus mill delivered prices.

Node	Path	Mill	Pulpwood cost $/cunit	Sawtimber cost $/cunit
1	1-3-5-8-9	8	-41.20	--
2	2-3-5-8-9	8	-41.20	--
3	3-5-8-9	8	-42.80	--
4	4-5-8-9	8	-41.20	--
5	5-8-9	8	-45.20	--
6	6-5-8-9	8	-41.20	--
1	1-3-5-7-10	7	--	-91.00
2	2-3-5-7-10	7	--	-91.00
3	3-5-7-10	7	--	-92.80
4	4-5-7-10	7	--	-91.00
5	5-7-10	7	--	-95.50
6	6-7-10	7	--	-93.70

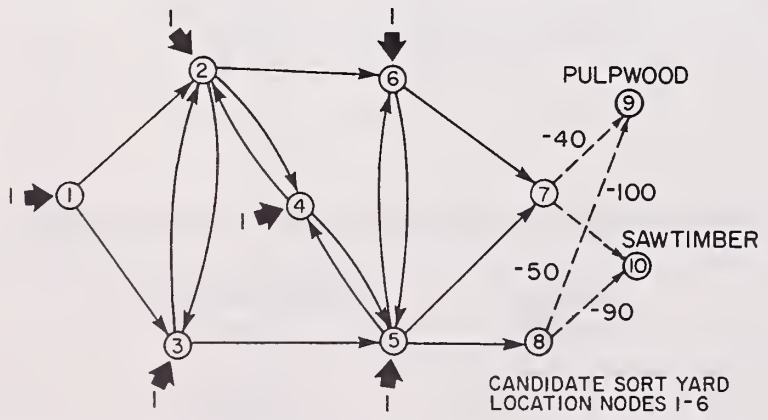


Figure 3.-- Network for phase 1 used to derive least cost path for one cunit of sawtimber and one cunit for pulpwood from each candidate sort yard location to the final destination for the respective product. The negative values indicate the delivered price each mill would pay for sawtimber and pulpwood.

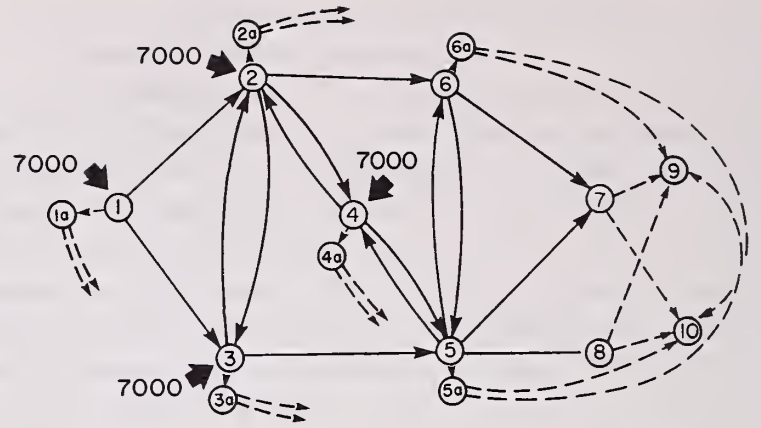


Figure 4.-- Expanded network for phase 2 showing added arcs from each candidate sort yard location to super destinations. Node 9 is the super destination for proportion j = 50/50 and node 10 is the super destination for proportion j = 30/70.

In phase 2, one "super destination" node is added for each proportion. Since we have two proportions in this problem, there will be two super destinations. Then one sort yard "investment node" (node 1a, 2a, 3a...etc., fig. 4) is appended to each candidate sort yard node and from this node two links are added to the network. The link from the candidate sort yard node to the "investment node" has a fixed cost and zero variable cost. The fixed cost equals the sort yard investment cost. The two links from the investment node to the super destinations use the information from phase 1. The descriptors for these links are a zero fixed cost and a variable cost. The variable cost is given by equation [1].

$$VC_{ij} = P_{pj} [HC_{pi} + SC_p - V_p] + P_{sj} [HC_{si} + SC_s - V_s] \qquad [1]$$

where:

VC_{ij} = the total weighted unit cost for transport of one cunit of proportion mix j from node i to the mill,

P_{pj} = the proportion mix j for pulpwood,

P_{sj} = the proportion mix j of sawtimber,

HC_{pi} = the transport cost per cunit over the least-cost route from node i to mill for pulpwood,

HC_{si} = the transport cost per cunit over the least-cost route from node i to the mill for sawtimber,

SC_p = the sorting cost per cunit for pulpwood,

SC_s = the sorting cost per cunit for sawtimber,

V_p = the delivered mill price per cunit for pulpwood,

V_s = the delivered mill price per cunit for sawtimber.

The expanded network for phase 2 is shown in table 6 and figure 4. In phase 2, the nodes 9 and 10 are super destinations. Now, however, node 9 is the super destination for all sources

Table 6.-- The link data for the expanded network. Negative costs are variable costs minus mill delivered prices.

Link from	to	Variable cost ($/cunit)	Fixed cost ($)
1	2	1.0	0.0
1	3	2.0	0.0
2	3	2.0	0.0
3	2	4.0	0.0
2	4	3.0	0.0
4	2	2.0	0.0
4	5	5.0	0.0
5	4	4.0	0.0
5	6	3.0	0.0
6	5	5.0	0.0
2	6	6.0	0.0
6	7	7.0	0.0
5	7	5.0	0.0
3	5	3.0	0.0
5	8	3.0	0.0
1	1a	0.0	40,000.0
2	2a	0.0	50,000.0
3	3a	0.0	40,000.0
4	4a	0.0	55,000.0
5	5a	0.0	32,000.0
6	6a	0.0	33,000.0
1a	9	-62.10	0.0
2a	9	-62.10	0.0
3a	9	-63.80	0.0
4a	9	-62.10	0.0
5a	9	-66.35	0.0
6a	9	-63.45	0.0
1a	10	-74.48	0.0
2a	10	-74.48	0.0
3a	10	-76.22	0.0
4a	10	-74.48	0.0
5a	10	-78.83	0.0
6a	10	-76.37	0.0
7	9	-65.00	0.0
8	9	-65.00	0.0
7	10	-77.00	0.0
8	10	-73.00	0.0

with the proportion mix j = 50/50, and node 10 is the destination for all sources with the proportion mix j = 30/70. In other words, there will be one super destination for each proportion; at most n super destinations if there are n proportions. The network for phase 2 is now complete. The solution to this network can now be obtained using mixed integer programming or heuristics. The solution for phase 2 is shown in table 7. One sort yard should be built at node 5 and wood from all source nodes should be delivered to the yard for intermediate processing. The information from phase 1 (table 5) is used to indicate the route and destination for the pulpwood and sawtimber when it leaves the sort yard. Pulpwood leaving the sort yard should go to the mill at node 8; sawtimber should go to the mill at node 7 (fig. 5).

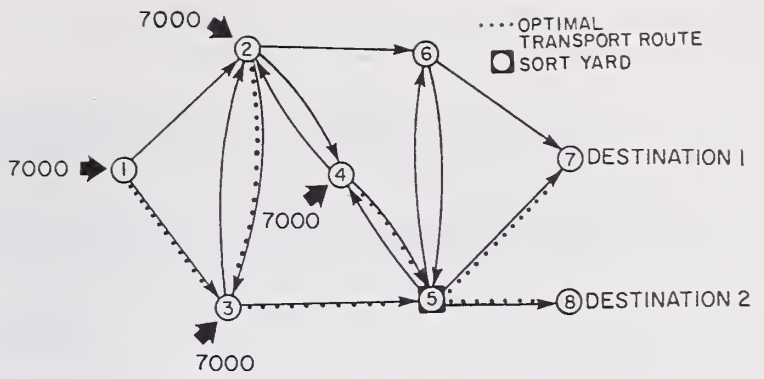


Figure 5.–Network showing transport routes with sort yard constructed at node 5.

Discussion

Using the two-phase modeling approach one can quickly identify the size of the network for each phase. For phase 1 the network size will be approximately the size of the original network plus dummy links to represent prices. For phase 2 the network size is primarily determined by the number of sort yards and the number of proportions. The phase 2 network will be approximately equal to the original network *plus* the sort yard investment links *plus* the product of the number of sort yards multiplied by the number of proportions. In other words a 1,000 link road network with 50 sort yard locations and timber arrivals categorized by 50 proportions would require approximately 1,000 + 50 + (50)(50) or 3,550 links.

Another variation of the sort-yard problem solves the operational question of which "proportions" should pass through a previously constructed sort yard. Once the initial problem of locating and constructing sort yards has been solved, the "investment" cost has occurred and the allocation of various proportions through sort yards or to final destinations is a significant operational concern.

A similar two-phase solution procedure without investment costs for the sort yard, but with sorting costs by piece size included, yields which proportions from various sources would gain in value over the returns from sending them to final destinations without sorting. The time frame from an operational standpoint would require using the model whenever the

Table 7.-- Solution for Phase 2. Negative costs are interpreted as positive profit since problem is being solved as cost minimization.

Node	Volume	Path	
1	7,000	1-3-5-5a-10	
2	7,000	2-3-5-5a-9	
3	7,000	3-5-5a-10	
4	7,000	4-5-5a-9	
			variable cost - $1,906,520
			fixed cost $ 32,000
			total - $1,874,520

"proportions" changed from sources, whenever relevant costs changed, or whenever product returns changed.

Regardless of the size or management, there is some limit to the number of pieces per unit time (day, shift, etc.) that sort yards can handle. Often, before the absolute limit is reached, sort yard managers use overtime resources or add more equipment to handle increases. These management practices may be modeled as alternative cost functions for the sort yard once certain limits are reached. The cost function might be shifted upwards to reflect overtime costs or it may be higher as well as change shape as additional equipment is added.

One way to model capacity limits is to expand the phase 2 network by including a capacity link between the investment node and the "proportions" node for each cost level. For three levels of costs (straight-time, overtime, and additional equipment), three capacity links would be needed and the number of arcs added to the network would be tripled. This formulation would be useful for operational planning to balance surges in production.

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A Systems Analysis Approach to Economic Feasibility Analysis for Forest Products Utilization

Thomas C. Marcin[1]

Abstract.--Systems analysis is often used in developing forest management plans and policies. This paper presents a conceptual framework for the systematic evaluation of forest product utilization technology in the context of the forest resource system. Emphasis is placed upon evaluating the economic feasibility of forest product utilization as a component of the forest resource management system.

This is a conceptual paper rather than a procedural paper. An expanded view of systems analysis is presented in an attempt to broaden thinking about what feasibility analysis means and how evaluation of forest products utilization might be improved--which is what system analysis is all about. The generalized view of systems analysis has been expressed by Casti (1987) as follows:

problems + tools + a world view = insight

Casti explains that an indispensable role is played by one's scientific *Weltanschauung* or "world view" in determining the nature and degree of insight that can be gained about any problem. When translating a problem statement into a formal mathematical structure, the world view is represented by the type of formal mathematical system chosen to reflect the features of the problem. In turn, this mathematical world view dictates the questions that can be asked and the tools and techniques that can be used to seek insights and answers (fig. 1). Furthermore, I will explain that a formal mathematical model is not required in every case and that judgment and extra rational variables can be considered because systems analysis is usually a mixture of qualitative and quantitative analysis.

The primary purpose of this paper is to recognize that forest product utilization and forest resource management are inexplicably intertwined in the forest resource system. The forest resource system, a set of interacting variables, is part of a larger system that is the sum of human experience and defines the value of forest resources (Duerr et al. 1979). It is obvious that in order to manage forests economically, timber and other biomass removals must be converted into products that are marketable at a price higher than the cost of producing the products. To accomplish this, the removals generally go through some type of conversion process. This paper attempts to provide a conceptual basis for the development of these broad concepts. I begin by providing a discussion of general system concepts and methodology. Then, I present a conceptual application to the forestry sector.

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System Analysis Concepts

There are probably as many definitions of systems analysis as there are systems analysts. The systems analysis concept presented here departs from previous system analysis literature in that a mathematical systems model does not have to be the central component of the problem solution. The central component of analysis may be quantitative, qualitative, or mixed, and it may be an expert person or a computer information system.

Methodological tools considered for systems analysis range from behavioral research into what exists, through values research into what is preferred, to normative research into what should be. Research efforts to demonstrate the three fundamental components of feasibility analysis--economic, technical, and socio-political--are difficult and ephemeral, either taken individually or considered together. Krone (1980) provides a statement of general system concepts that also reflects my view:

> "A system is defined as a set of interacting elements. The systems approach provides understanding and comparisons within and between systems. Systems analysis is a set of techniques that are qualitative, quantitative, and mixed-deriving methodologies from the scientific method, systems philosophy, and branches of various scientific disciplines dealing with the phenomenon of choice. Systems analysis incorporates both explanatory and prescriptive methodologies."

A system is a collection or arrangement of entities or things related or connected such that they form a unity or whole. Some entities are retained in the system or are endogenous, while others are transient to it. Transient entities are generally input to the system and undergo some conversion process and, subsequently, output from the system. During the time they are in the system, they are part of the system. However, before and after they are in the system, they are external. Anything external is referred to as the system environment (Wetherbe 1984). The major benchmarks of the performance of a system are improvement of the quality of a system as evaluated and measured against standards consciously selected, and the feasibility and desirability of improvement or redesign possibilities. Systems analysis is a major instrument for this purpose.

Conceptualizing appropriate analysis models for complex problems is an essential macro tool of the systems analyst. This section provides conceptualization and structure for the identification and management of knowledge prerequisites for technology and transfer. The knowledge for systems applications can be classified into the following three categories:

1. *Environmental knowledge* is about the understanding, control, and direction of the environment. This knowledge falls predominantly into the physical and natural sciences.
2. *Human knowledge* is about the understanding, control, and direction of individuals, groups, and society. This knowledge falls predominantly into the social, behavioral, and life sciences.
3. *Control knowledge* is about the use and further development of knowledge within the first two categories.

PROBLEMS + TOOLS + A WORLD VIEW ▪ INSIGHT

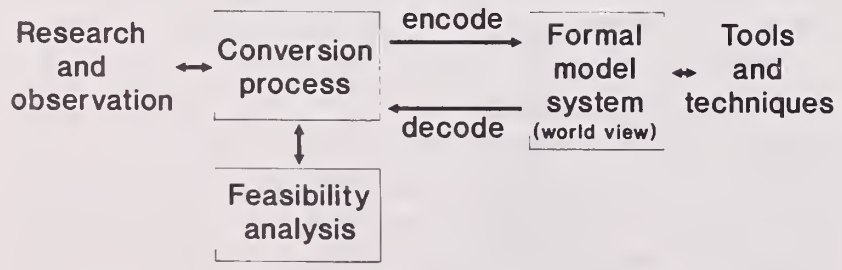


Figure 1.--The systems view as related to formal mathematical structure.

Knowledge is defined as tacit or explicit. Tacit knowledge is obtained through living and is unformulated, personal, experiential, nonexplicated, and involves the Gestalt process. It is basic to human understanding, knowledge, and as a predominate determinate of culture for the transmittal of knowledge from one generation to the next. Expert knowledge is a combination of explicit and implicit knowledge. It is the extra rational component of culture that is represented by emotion, prejudice, and societal attitudes. Explicit knowledge is obtained through learning and is articulate, public, objective, logical, and forms the basis for the disciplines of learning. The articulate framework for culture displays facts in words, symbols, formula, maps, and other technical methods of expression.

Scientific knowledge is viewed by Kuhn (1962) as growing within normal science through the aggregation of information consistent with a theory or replacement of one theory with a successor theory. He describes the process where normal science develops a paradigm or a universally recognized and accepted body of knowledge. This paradigm, for a time, provides solutions to problems for a community of scholars or practitioners. Over a period of time, research and practices begin to reveal anomalous facts unaccounted for in the theory. This stimulates new scientific discoveries and creates a crisis of credibility in the paradigm. A new theory emerges that precipitates a scientific revolution or a nonaccumulative developmental episode in which an older paradigm is replaced in whole or in part by an incomplete new one, often with traumatic and long-range impacts on science, or scientists, and on society. Ample historical evidence in the physical sciences validates this theory. Reflections upon social sciences and the arts also reveal interesting insights when viewed through Kuhn theory (Krone 1980).

The scientific method where human systems knowledge is increased, generated, applied, and analyzed, is diagrammed by Krone as shown in figure 2. It has its conceptual beginning in the prevailing scientific paradigm where the Kuhnian process can be transformed by the process itself. The process of scientific knowledge accumulation is more complicated than this simplified diagram, but the essential features are there. An important key to this approach is the evaluation and verification for a particular problem-orientated systems analysis by real world performance over time. This macro validation process is important to avoid closed and tautological systems for science, management organizations, and problem-orientated systems. A major distinction between the scientific method in systems science and the pure scientific method is the inclusion of the decision maker. At some point in a real world system a decision on policy or action must be made. It may be based on scientific considerations or upon other considerations. In this case, it is that of making feasibility analysis in the context of the overall forest resource system. The task here is to bring together the best scientific information in a systematic fashion and to present it for evaluation. The system concepts in this paper fall into the category of research and analysis in the center of figure 2.

Quantitative Tools for Systems Analysis

Quantitative measurements allow us to organize knowledge, to compare results over time and space, to use mathematical methods to test hypotheses derived from scientific theory, to optimize system performance based upon alternative criteria, and to simulate present and future system output. It allows aggregation and manipulation of data in management information systems using more powerful and accessible computers.

Quantification allows reduction of the complexity to understandable levels for making decisions. It provides justification for stipulated system output. Through quantification we record events for later review, evaluation, comparison, and validation within the scientific method. We can design feedback mechanism for control and decision making by quantifying reports, relationships, and events over time. Simulation is possible with quantification. This requires a structured, rational, and repeatable process, capable of sensitivity analysis by adjusting quantitative independent variables for analysis of alternative outcome arrays. Useful relationships can be observed through mathematical and statistically derived transfer functions. Quantification is necessary, although it is not sufficient to measure the efficiency, effectiveness, and quality of the systems. Systems analysis is impossible without some degree of quantification. The ability to abstract the physical and social world into quantifiable models has been a major contributor to scientific, technological, and social progress. In summary, we must quantify to understand or improve human systems.

An important aspect of the success of a modeling effort is the choice of the correct mathematical structure to represent the system under study. This surrogate system must be representative of the "real system" and of the problems to be solved by decision makers or managers in a realistic manner. It is convenient to represent the set of mathematical paradigms into four principal components (Casti 1987). These categories are operations research (OR), computer science (CS), control theory (CT), and systems theory (ST). These specific techniques can be further classified as deterministic or stochastic.

THE SCIENTIFIC METHOD IN SYSTEMS ANALYSIS

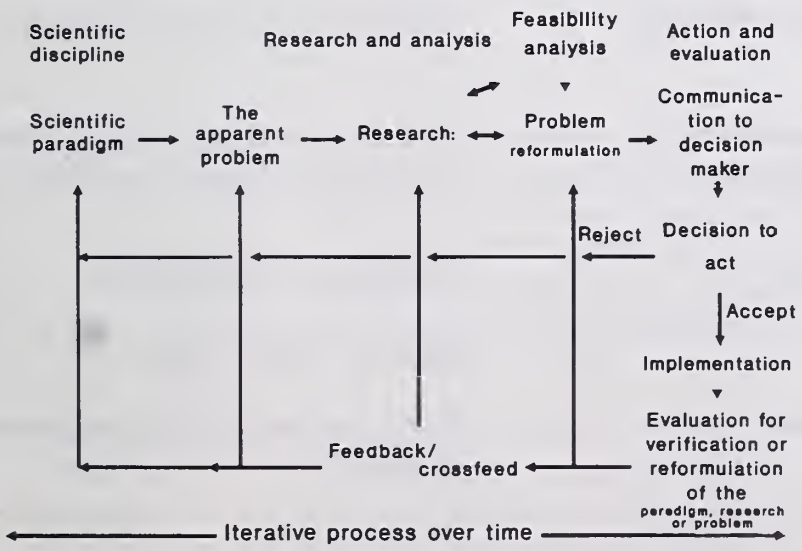


Figure 2.–The scientific method in system analysis as diagrammed by Krone (1980).

Operations research problems generally revolve around issues of planning, scheduling, and resource allocation. Methodologically, the techniques used are traditional OR tools: resource allocation, scheduling theory, inventory control, and decision analysis. Control theory, derived from aerospace and mechanical engineering problems in the 1960's, contains the concepts of system feedback, adaptive change, uncertainty, and complex hierarchy. Computer science has developed operating systems and new computer languages to be used to manage information and in conjunction with artificial intelligence or expert system techniques. These systems can also be used with OR or CT methods. Generally speaking, these models or tools are techniques of OR, CT, and CS. They start with a particular formal structure as listed in table 1 and analysts try to adapt problems to them. The basic problem revolves around how various applications can be addressed within the selected paradigm or technique.

System theory, on the other hand, differs in an important way from conventional operations research or management science methods. A systems theory world view focuses more upon paradigm construction than upon techniques and algorithms associated with a given framework. You start with the framework or point of view and explore how important concepts or issues might be addressed. The object of the systems view is to develop a set of techniques or paradigms that meet the objects of the system that may include some of the quantitative tools or methods in table 1. For example, Casti (1987) begins with the concepts of complexity, flexibility, self-repair, adaptability, self-regulation, reliability, resilience, and performance in his definition of the manufacturing process as a system. He then looks for an appropriate paradigm for the manufacturing system in a relational rather than structured way.

The indiscriminate and inappropriate use of quantitative tools has been greatly aided by the plethora of computer software that simplifies applying without necessarily implanting any understanding of underlying theoretical principles. As Wetherbe (1984) states:

> "First it is important to understand the difference between theory and technique. Theory is really nothing more then the notion or ideas about how things work or the way things are. Techniques are just different methods or approaches to perform different tasks. Ideally techniques should be based upon theory...Someone who knows technique without theory is potentially a dangerous person...Anytime someone uses a particular technique without knowing the reason for the theory behind it, that person is apt to use the technique when it is inappropriate."

A common criticism of the educational process is that it tends to teach students how to do exercises rather than how to solve problems. For example, we teach students how to write a computer program, how to solve a mathematical equation, or

Table 1.--Quantitative models and techniques in systems analysis. Source: Krone (1980) and author's interpretation.

Model or technique	Application	Knowledge base
	Deterministic models	
Linear programming	Allocation, distribution, and optimization in business, transportation, inventory, construction,logistics, and networks	Computer science, sensitivity analysis, algebraic solutions simplex tableau, and economics
Queuing theory	Waiting, services ratios and people, things, events	Monte Carlo, simulation, and statistics
Program management techniques	Production and construction planning	PERT (cost or time) GANTT charts, network analysis (CPM), and decision trees
Markov analysis economics	Marketing, sales, forecasting	Matrix algebra and economics
Conflict analysis	Business and psychology	Game theory
Quality assurance	Industry, defense	Technology and science
Cost/benefit	Resource allocation	Economics and statistics
	Probabilistic Models	
Dynamic programming	Multistage decision in production, allocation	Computer science and probability theory
Computer simulation	Systems interactions	Computer science and Monte Carlo
Probabilistic inventory models	Where demand and/or lead time are random	Probability theory and expected value statistics
Stochastic models	Computing probabilities of systems transition	Matrix algebra and calculus
Sampling, regression, and exponential smoothing	Problem solving with large populations	Statistics and probability theory
Bayes theorem	Forecasting under conditional probability and dependence, causal analysis	Algebra, probability theory, and knowledge of prior probabilities
Cost and benefit analysis	Resource allocation	Economics and statistics
Fault tree analysis	Systems behavior	Algebra and statistics
Artificial intelligence and expert system	Systems management	Computer science and cognitive science

[1]*Models that are applicable to problems where there is only one state of the world assumed and where variables, constraints, and alternatives are, after acceptable assumptions, known, definable, finite, and predictable with statistical confidence.*

how to do a financial analysis. The students, however, often do not know when it is appropriate to apply these techniques. This is similar to the story of the student who is taught how to use a screwdriver--the screwdriver being symbolic of a technique such as computer programming, linear programming, or net-present-value analysis. Upon being employed, the student is excited about applying the screwdriver to screws that need to be tightened. The new employee goes about the organization looking for screws to tighten and tightens them. Eventually, however, there are no screws left to be tightened. Looking for new opportunities to apply the skill of using a screwdriver, the employee gets out a hacksaw and starts filing slots into the heads of nails. As silly as this story may seem, it is unfortunately representative of applying inappropriate techniques to the solution of a problem.

Quantitative tools and techniques reduce uncertainty and provide valuable optimization techniques for decisionmakers. However, only limited application has been found in research and development management in large corporations because of data limitations and mistrust of autonomous optimization algorithms (Twiss 1980). As important as quantification is to removing uncertainty and guiding management decisions, the art of quantitative systems analysis still lies in the analysts' and decision makers' ability to judge which uncertainties are being removed advantageously and, conversely, which ones fit the Procrustean metaphor. Correctly applying quantification will usually make the difference in whether system goals are met. Krone (1980) presents a summary of potential pitfalls in the use of quantitative techniques in table 2.

Table 2.-- Some pitfalls in the use of quantitative models and techniques. Source: Krone (1980) and author's interpretation.

Adapting the problem and the real world to fit the formula (the Procrustean metaphor).
Model reification (fascination and preoccupation with details of the model, while being overcome by events in the real world--"seeing the trees and not the forests").
Ignoring the axiom of "appropriate methods for unique problems."
Overconfidence and oversell.
Oversophisticated models and techniques requiring non cost and benefit allocation of resources.
Using the wrong model for the problem.
Using the right model incorrectly.
Tautological solutions (those highly sensitive to the statement of the problem and methodology employed).
Making a Butch (Herman Kahn's "completely mistaken technical notion or fact"1).
Interest in only the worth (economic utility) of the outcome and not the values of the system.
De-emphasis or ignorance of qualitative or extra rational components because of relying on mathematics and associated rational models of policy making.
Overuse of technical or mathematical language, thus failing to communicate.

[1]A classic cross-cultural Butch was the translation of President Carter's welcoming statement in Warsaw, Poland, in 1977 from "I have a desire for peace" into "I lust for Poles."

Qualitative Analysis and Expert Judgment

Well defined and documented quantitative analysis is the preferred method of analysis and problem solution. However, this limits the appropriate set of problems to which these techniques will work, and the smart analyst or scientist will avoid those that do not fit the assumptions or algorithms (e.g., the so-called fuzzy systems). Conclusions drawn in the absence of quantitative measurement will have doubtful validity. On the other hand, action taken solely on the basis of quantifiable variables can lead to inappropriate, wasteful, noneffective, or undesirable results (Krone 1980). Fortunately, the choice is not an either or one, but one of sensible use of both quantitative and qualitative tools in an intelligent manner to enlighten decision makers rather than to obfuscate the problem. The central component of the analysis may be quantitative, qualitative, or most likely a mixture of the two. As Krone states:

> "The object of including explicit qualitative methodologies is to provide analysts and decision makers with a rational means for the inclusion of those qualitative and often extra rational--variables in the analysis. The problem for the analysts is not whether those qualitative variables do exist in human systems. They do exist. The problem is how to rationally consider those variables on the assumption that the alternative is for them to remain implicit and unanalyzed, while they continue to move systems toward quality improvement or deterioration. If their influence is toward improvement, we would like to know more about the functioning of those variables so the process can be continued, expanded, and duplicated in other systems. If the influence is toward deterioration, we want a capability for identification, evaluation, and rectification before system failure becomes irreversible. We cannot cure an unknown system pathology. One lesson of the 20th century is that hidden pathologies tend toward system breakdowns rather than self-amelioration."

The idea here is to determine quality as measured against some standard that is measurable and can be explicated. The methodology is conceptually very simple but operationally

often complex. The theoretical process involves two steps: (1) determine the quality using criteria and (2) judge that quality by comparison with standards. One important way to incorporate subjective or tacit knowledge in a system is by cognitive science using expert systems (Cleaves et al. 1987). Farnum and Lembersky (1987) found that by incorporating managerial judgment into a large simulation system that they called "this system of manual optimization," there was a better understanding of the process by management decision makers and a more realistic definition of problem objective functions and constraints.

The primary criterion is the dependent variable, stated in overall terms, for determining quality of a system in evaluation. The total net desired output is determined by it. It is not usually easy to measure, therefore, this requires the establishment of secondary criteria that are subcomponents of a system chosen for evaluation because they are correlated with and more measurable than the primary criterion. The secondary criteria become independent variables to shape the quality of the net output. They are components of input such as people, raw materials, structure, process, or output for evaluation. The primary criteria are organizational effectiveness, goals, or strategies.

Take care in choosing secondary criteria so that what you select is not just convenient to measure and that the resulting numbers fit conveniently into mathematical or economic formulas or into computer programs. There are always alternative standards to measure the quality and whether the primary goals of a system are met. Standards may be derived from both rational and extra rational variables. It is usually better to explicitly include extra rational components in the system whenever possible, because it is analytically useful to consider whether they are positive, neutral, or negative in the performance of the primary system objective. This brings us to the concept of systems leverage, which accounts for the fact that small improvements in one or more components can have significant leverage effects but in opposite directions. This is why the selection and continued review of secondary criteria for evaluation are important to the success of an enterprise. For example, if the lack of effective marketing of products produced is a limiting factor of profitability of an enterprise, a marketing initiative may be needed. Similarly, research on new residential building systems may not be effective because of restrictive building codes, lack of financing by mortgage companies, and consumer preferences for traditional housing.

Feasibility Analysis

There are two main tasks for our conceptual approach to feasibility analysis. First, to design the overall system in which the feasibility analysis subsystem is embedded, and second, to define the particular systems framework for feasibility evaluation. To place our analysis in the proper perspective, we will look at methodological considerations.

There are three fundamental and interrelated categories of research methodologies for systems analysis: (1) behavior research, (2) value research, and (3) normative research. There are also three basic categories of feasibility: (1) economic, (2) technical, and (3) socio-political. These categories of research and feasibility analysis are all interrelated in determining the system design and subsequent problem statement. Economic feasibility is the probability that economic resources are available to meet the goals of the system. Within economic feasibility analysis, it may be important to conduct a marketing feasibility study. Also included are the economical development of resources and the economic assessment of conversion processes that can efficiently produce products that are acceptable to the consumer. Technological feasibility is the probability that the scientific and technical development goals of the system are met. Socio-political feasibility is the probability that the policy or technological alternative will be acceptable to the user, decision maker, or society.

Feasibility of the conversion process, in the context of the overall resource system, is the principal concern of this paper. The economic feasibility of resource conversion is the particular subsystem that I will examine. Economic feasibility is related to technical and socio-political feasibility as well. The three feasibilities are mutually supportive even though they may use data from different sources. Economic feasibility has a great deal to do with the status of technology; technology is partially dependent upon budgets for research. Political feasibility may be determined by professional technological or economic feasibility studies. Care must be taken to consider this interdependence when conducting feasibility analysis. Economic feasibility will also interface with the available resource system and the market and consumption systems.

There are several steps in the economic feasibility analysis. The first is assessment of a need, the second is project definition, and the third is project evaluation. The first step is to identify the need to be met by the project and then to define the system goals for the project. For example, economic development may be a system goal. Utilization of a surplus forest resource, such as eastern hardwoods, may be another type of goal. The establishment of need, such as the ability to compete economically or establishing community stability through resource development, can then be translated into specific goals of greater utilization of northern hardwoods in the United States. This goal then needs to be made operational by the establishment of criteria for evaluation and measurement.

The appraisal criterion is then an important factor in determining the type of project selected for feasibility evaluation. The following criteria may be required for project evaluation: (1) organization objectives, policies, and values; (2) market needs, consumer acceptance, and marketing; (3) research and development; (4) financial; (5) production or process; (6) environmental or ecological; and (7) social and political acceptance. Note that net output can be misleading as a criterion because it measures the wrong thing. For example, if return on investment over time is allowed to become the primary criterion of a

business organization as opposed to a broader criterion of organization health and productivity, a secondary-to-primary criterion transformation has taken place that could be costly, risky, or even fatal (Krone 1980). A similar problem can exist when return on investment is used as the primary criterion to justify environmentally unwise projects in some developing countries. As Gold (1988) states:

> "The most common approach to evaluating prospective technological innovations involves two steps: evaluating their expected cost savings and revenue increase relative to current capabilities; then comparing resulting gains (discounted to determine their present net value) with their investment requirements, i.e., the usual capital budgeting approach. But this essentially is the wrong criteria.
>
> "After all, the basic objective in adopting major technological innovations which embody significant investment for many years must be to safeguard or improve a firm's competitiveness over an extended future."

"For a public enterprise the main goal is to provide benefits for the nation and to improve the national efficiency," to quote Gifford Pinchot. To do this all the components of the system under study must be scrutinized. This includes all the inputs to the conversion process over time.

According to Clifton and Fyffe (1977), a complete study of project feasibility includes: (1) market analysis, (2) technical evaluation, (3) a financial analysis, and, if needed, (4) a social profitability analysis. The market analysis involves the search for an analysis of data that can be used to identify, isolate, describe, and quantify the market. This study can be used to identify user needs. A market study generally should contain: (1) a brief description of the market, (2) an analysis of past and present demand, (3) an analysis of past and present supply, (4) estimates of future demand for the product, and (5) estimates of market share both domestic and foreign.

Technical analysis serves to establish whether or not a project is technically feasible or what research needs to be accomplished to make it so. It also provides a basis for cost estimating. The technical analysis should contain a review of techniques or processes to be applied and include: (1) description of the product, (2) description of selected or desired manufacturing process, (3) determination of plant size and schedule, (4) a study of available raw materials, (5) an estimate of labor requirement, (6) a plant location study, environmental costs, and (7) estimates of production cost for product.

Financial analysis concentrates on determining whether a project is profitable from a commercial standpoint or whether a project achieves a minimum threshold rate of return and on the amount of capital required to implement it. Information from the market and technical analysis is used to determine financial measures. A sensitivity analysis or risk analysis may also be conducted. For new projects an estimate of total project costs, capital requirements, and cash flow is desirable. An analysis of rate of return on investment and price sensitivity is also needed. A sensitivity analysis and risk analysis may be made to identify items that have a large impact on profitability.

Finally, a social profitability analysis may be performed if there is public involvement or there are established national priorities. The social profitability analysis is an evaluation of the contribution of the projects to the economy. This includes the evaluation of the project toward meeting goals such as increasing employment or net foreign exchange benefits. This may include goals of increasing markets for wood products or improving national competitiveness. Generally. some cost-benefit analysis is used in conjunction with these social objectives.

The Forest Resource System

This paper concentrates on the relationship of forest product utilization technology to the analysis of economic feasibility of forest product development that in turn is related to forest resource management. The concept of the forest as a system as explicated by Duerr et al. (1979) is useful here. They state:

> "A major aim is to focus the work upon integrated forestry: the creation and use of all forest values from scenery to wood. We have tried to see forestry as a system of interacting variables and also as a part of a larger social system that in the final analysis is the sum of human experience. Another aim is to view forestry not as a set of rules, but as a set of resource alternatives. Still another is to demonstrate how modern quantitative methods of generating information can fortify judgement in choosing among resource alternatives."

Thus, the forest can be viewed as a social-biological-engineering system. We can also define three major components of the overall forest resource system: the timber-output system, the technologically defined conversion system, and the marketplace where the consumption interface occurs. The forest resource system is dynamic, that is, it changes continuously through time in many dimensions--biological, technological, economic, socio-political--that are changed by humans through management activities. Most systems analysis studies in forest resources concentrate on the timber-output system. This system usually has four subsectors: timber inventory, timber growth, timber management, and timber removal. This is the major part of the timber resource system from the foresters viewpoint. However, from an overall systems analysis viewpoint the other components, the forest product conversion system and the market and consumption interface are also important as are the interactions between the subsystems through time.

This paper concentrates on the forest product conversion system in the context of the overall forest resource system. The conversion process for forest resources is part of the overall forest resource system (Bethel and Schreuder 1976). The material supply operation is a function of the match between the

resource and the conversion and marketing system available to the resource. If the material being recovered is very valuable (e.g., gold, platinum, or silver), a relatively inefficient materials recovery system involving large expenditures of capital, energy, and labor per unit of material output may be economically feasible (Bethel 1980). Though it is not always recognized, a similar situation exists with forests. The total biomass of the forest is available for utilization at a cost. This includes trees, stems, branches, and even stumps and roots. Trees too small, crooked, or of the wrong species are also available. Mill residues, such as bark, slabs, edgings, trimmings, core, clippings, and round up, are also available at the conversion stage. According to Bethel, a utilization efficiency can be defined for a wood material supply system as the mass of material produced by the system as a fraction of the total stem biomass of the forest. Analogous to the metal materials supply system, a forest-based system can have low efficiency for high-valued materials like black walnut, mahogany, or rosewood. But, the efficiency must be much higher for low-market value material if it is to be economically feasible.

The forest-based materials supply is biologically renewable and therefore can change through time. Manipulation of the forest on the one hand and the manufacturing facilities on the other hand permit progressive improvements in utilization efficiency. A large simulation model was developed by Farnum and Lembersky (1987) for Weyerhaeuser Corp. that illustrates the interrelation between timber and conversion technology. The model was used to derive normative timber management strategies for future plantation based upon alternative growth and mill conversion assumptions. The model had four modules: biological growth and yield, harvesting and handling cost and productivities, mill conversion recoveries and values, and financial returns. A combination of an approach using judgment based on managerial experience was used rather than strict mathematics to develop a system of manual optimization. Using this system, they showed how advanced sawmill technology using small logs would provide a superior alternative to the conventional utilization and management systems.

These opportunities for change in the system permit reaction to changes in market preferences and conversion technology. Changes in the forest-based material supply system occur slowly over long time periods and generally require considerable expense. Bethel (1980) cites an example of such a system applied to tropical hardwoods. It includes a reference material system (RMS) as the integrating and synthesizing component (Bhaget and Hoffman 1980).

This illustrates the systems analysis approach to economic feasibility analysis for forest products utilization. With the use of process conversion models and proper data, the forest materials supply system can be evaluated in terms of utilization efficiencies. The results can be portrayed in the form of RMS. In a similar way, the flow of capital, energy, and labor can be evaluated through the material production system. Environmental considerations can be considered as constraints on the system.

Technology changes occur over longer periods of time. These technological changes influence wood utilization efficiencies. The rate of technological change can be effected by forest products research efforts. Therefore, technological change and research components are also included in the concept of systems analysis through time or a dynamic systems analysis.

The Forest Utilization System

The conversion or manufacturing process can be viewed as a system-determined science (Casti 1987). The conversion process is a multifaceted system that can be viewed from a number of perspectives of the overall process. The conversion process system can be expressed in a hierarchical fashion with raw materials being the lowest level and values the highest. What determines a systems problem in manufacturing is the relative emphasis upon issues of process and function, grounded in constraints from the natural resources, requiring a knowledge of several disciplines.

The concept of process implies that all of the inputs to the conversion process should be considered for change. A new machine or a method of organization that reduces the cost of production and thereby increases the efficiency of producing an existing product is just as important as development of a new product. The weakness in process technology in the United States has been pointed out by Thurow (1987).

The conversion process in forest products is typically product orientated. The customers or end users are not generally considered in this mold. Marketing considerations for customers holds that products are not an end in themselves but merely the means to satisfy the customers needs or desires. Feasibility analysis begins with the determination of research studies to satisfy identifiable human needs. This considers the process as being the conversion of scientific knowledge directly into the satisfaction of customer need in the market and consumption interface. The product then becomes merely the carrier of the technology and the form is only defined after the technology and the need have been clearly matched. Similarly, available forest resources should guide technological feasibility for particular regions.

Conclusion

The production of timber products generally leads to preoccupation with things rather than the concept of process. Forest industry is perceived as a process that converts raw materials from the forest into products, which in turn are converted into money by selling to customers who are willing to pay more for these goods than it costs to produces them. The margin between the price paid and the cost to produce yields is the profit that can be reinvested to sustain growth of the industry and provide wealth to shareholders directly and to society indirectly.

Most analysis and planning systems are resource driven. The viewpoint of this paper is that they should be driven by market and consumption systems and the technology and conversion systems, which may be a constraining factor and can be changed by research or technical development. The resource system is also modified by cultural activities, environmental change, and other biological factors. Capital investment and prospective future investment are also important factors. Existing establishments tend to want to prolong the status quo and maintain vested interests. What is needed is an outside look that utilizes available resources and ideas (Drucker 1988).

Business-driven resource decisions are viewed as generally preferred to those based only on timber-output system decisions. Better yet are ones in which the biological and resources system interfaces with a market and consumption system and a conversion and technology system. A good example of business-driven strategy is the development of the composite panel products, like waferboard utilizing aspen that was a surplus resource and was inexpensive to grow in the Midwest. High-cost plantations of red pine might have been the conventional resource manager's alternative for forest development in the 1950's. Systems analysis provides a way to look at forest resource management and development and broaden the perspective of the management decision making when looking at factors other than the resource base.

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Relating Network Analysis Results To Data Uncertainty In Forest Development Applications

Thomas L. Moore, John Sessions, and Robert Layton[1]

Abstract.--Network analysis in forest development applications often assumes perfect information. Monte Carlo simulation is used to test the sensitivity of network analysis results to uncertainty in the data for five forest development network problems. Two of the five areas are found to be very sensitive, two are moderately sensitive, and one network is insensitive to uncertainty in the input data.

To test the sensitivity of network solutions to uncertainty of the data, five typical transportation planning problems were identified from various regions of the USDA Forest Service. Input from the field units consisted of the estimated timber volumes to enter the source nodes, estimated transport costs, and estimated road construction costs.

It is assumed that the field data for the log volumes entering each node and the road construction costs are means of normally distributed random variables. The variance given for the random variables was based upon our experience of the uncertainty that could be expected in the field. One hundred variates from each distribution were chosen and the network solution which minimized road construction and transport costs was determined for each set of randomly selected timber volumes and road construction costs. The number of solutions with common paths were then identified. The frequency of occurrence of the solution identified using the original estimates indicates the sensitivity of the network to uncertainty of the data.

Although the analysis presented here could be used for any network analysis application involving fixed costs per link (arc), variable costs per unit flow per link, and units per source node, this analysis focuses on forest development problems.

Background

Network analysis is frequently used in forest development planning to determine the most economical network of roads to construct and the routes over which to transport logs from the forest to the sawmill or other destination. The sources where logs enter the transportation system are tracts of timber in the forest, and the sinks or destinations are the manufacturing facilities. The data in the analysis specifies the volume of logs entering the source node, the cost of road construction alternatives to access the sources, and the cost to transport the logs from the sources to the destinations. The road construction costs are referred to as "fixed costs" and the transport costs are called "variable" costs. The road and route optimization problem is known as the "fixed charge" problem in operations research. It is usually solved by either mixed integer mathematical programming or by the use of a heuristic method. Several network analysis programs are commonly used by the USDA Forest Service. These programs include: NETWORK, MINCOST, TIMBER TRANSPORT, and the TRANSHIP model and are described by Moore (1987).

Study Areas

Five study areas, varying in size and complexity, were selected from national forests throughout the United States. The study areas are referred to as: Off Planning Area (fig. 1), Gifford Pinchot National Forest, Washington; Peavine Planning Area (fig. 2), Eldorado National Forest, California; Silver Planning Area (fig. 3), Nezperce National Forest, Idaho; Kosciusko Planning Area (fig. 4), Tongass National Forest, Alaska; and Beaverdam Planning Area (fig. 5), Cherokee National Forest, Tennessee. Important characteristics of each network are shown in table 1.

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OFF PLANNING AREA CODED NETWORK

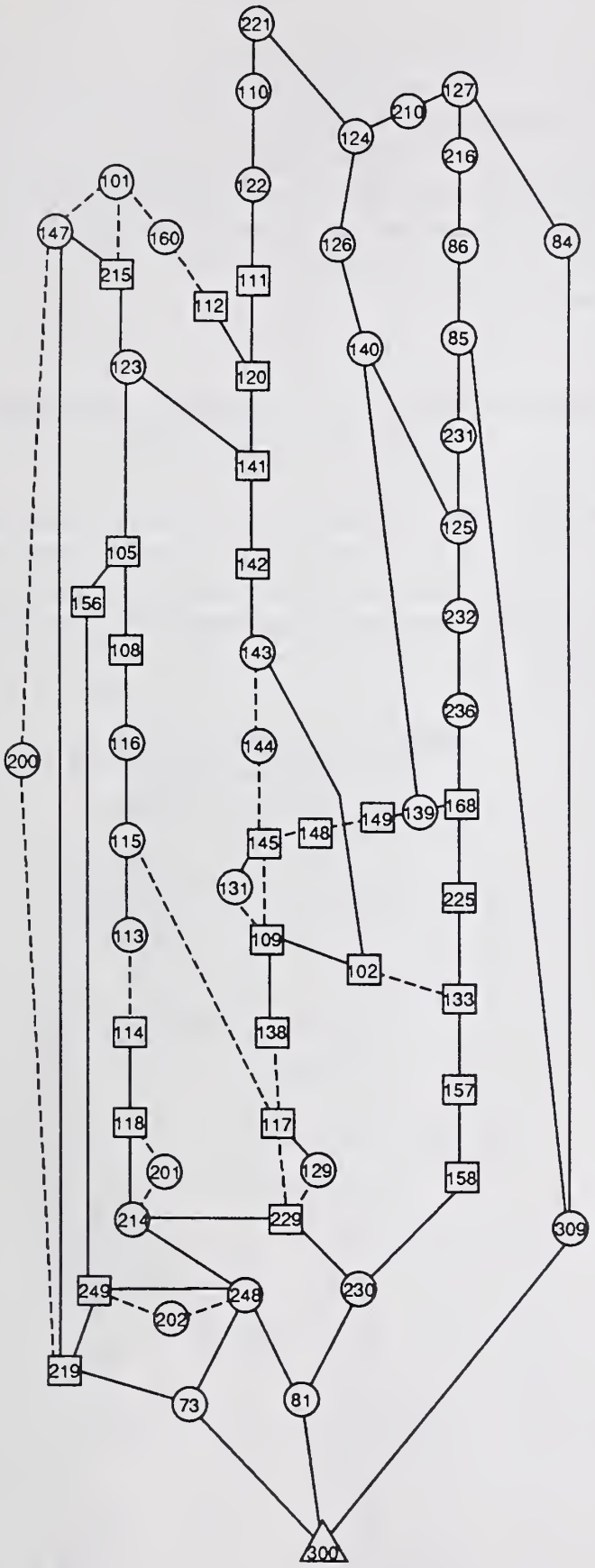


Figure 1--Network schematic for Off Planning Area.

PEAVINE PLANNING AREA CODED NETWORK

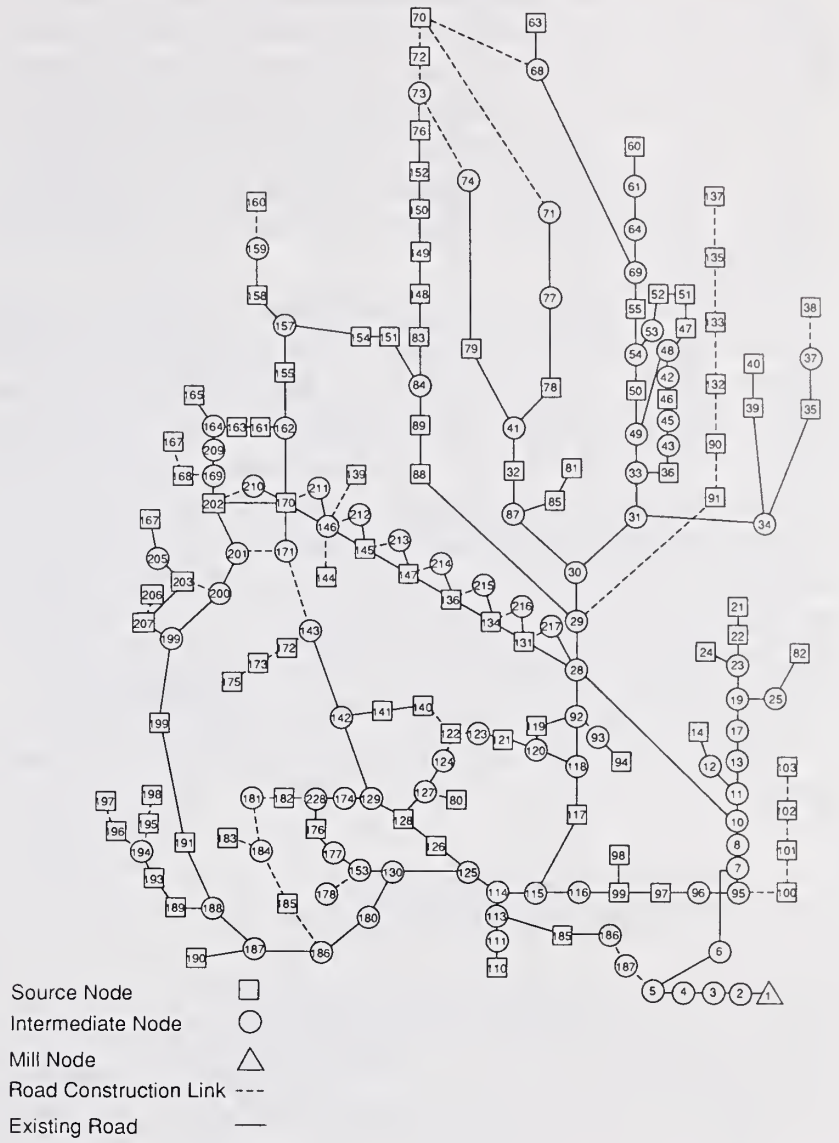


Figure 2--Network schematic for Peavine Planning Area.

Description of Sensitivity Analysis

Data collection for a network analysis study can be difficult and expensive. The quality of information needed for the analysis to be meaningful is generally unknown. The analysis could be invalid if the data estimates were significantly different from the actual values occurring in the field at the time of implementation. Errors, to some degree, are expected for every item of data used in the analysis. Therefore, the question is "how much error can reasonably be expected in the data and how do these errors affect the results?"

Monte Carlo simulation (Degarmo et al. 1984) is used in this analysis as a technique to aid in estimating the quality of the results. The original data are assumed to be the means from normally distributed random variables. The standard deviations are estimated from previous Forest Service experience. The ratio of the standard deviation of the timber volumes to the mean (coefficient of variation) is assumed to be 0.3. Similarly, the fixed costs are assumed to have a coefficient of variation of 0.2. The variance of transport costs is not considered in the analysis because the Forest Service collection schedule for transport costs is fixed.

The network from each planning area is then analyzed 100 times, each time substituting variates from the assumed distributions for the timber volumes entering the network and the construction costs for proposed links. The NETWORK program was used because a previous study evaluating the performance of several network analysis models using these five study areas showed the NETWORK program provided the best results (Moore 1987).

Each of the 100 scenarios (simulations) and corresponding solutions represent one possibility for the true optimal solution when the project is implemented. A different set of solution paths might result from each simulation or all of the 100 solutions might be the same. The frequency with which the solution paths change represents the sensitivity of the individual network. The "Stability Index"[2] indicates the sensitivity of the network to variability in the input data. The Stability Index is defined as the percent of total simulations run having the same solution paths as those chosen by an analysis using the original data (means). The Stability Index value is calculated as:

$$\text{Stability Index} = \frac{\text{No. of Simulations w/Original Sol. Paths}}{\text{No. of Simulations}} * 100$$

A Stability Index value of 1% indicates that only one of 100 simulations arrived at the same solution identified using the original data. A Stability Index of 100% indicates that all simulations have the same solution as the original solution. The "Maxsim" value is the percent of simulations having the largest number of identical solutions. This value is calculated as follows:

$$\text{Maxsim} = \frac{\text{Maximum No. of Identical Simulations}}{\text{No. of Simulations}} * 100$$

The Maxsim value is significant because it may identify a solution set that has a higher probability of being selected than other solution sets. The Maxsim value can never be lower then the Stability Index value, and in many instances, they will be identical.

[2]More (1987) refers to this value as the Sensitivity Value in earlier paper.

SILVER PLANNING AREA
CODED NETWORK

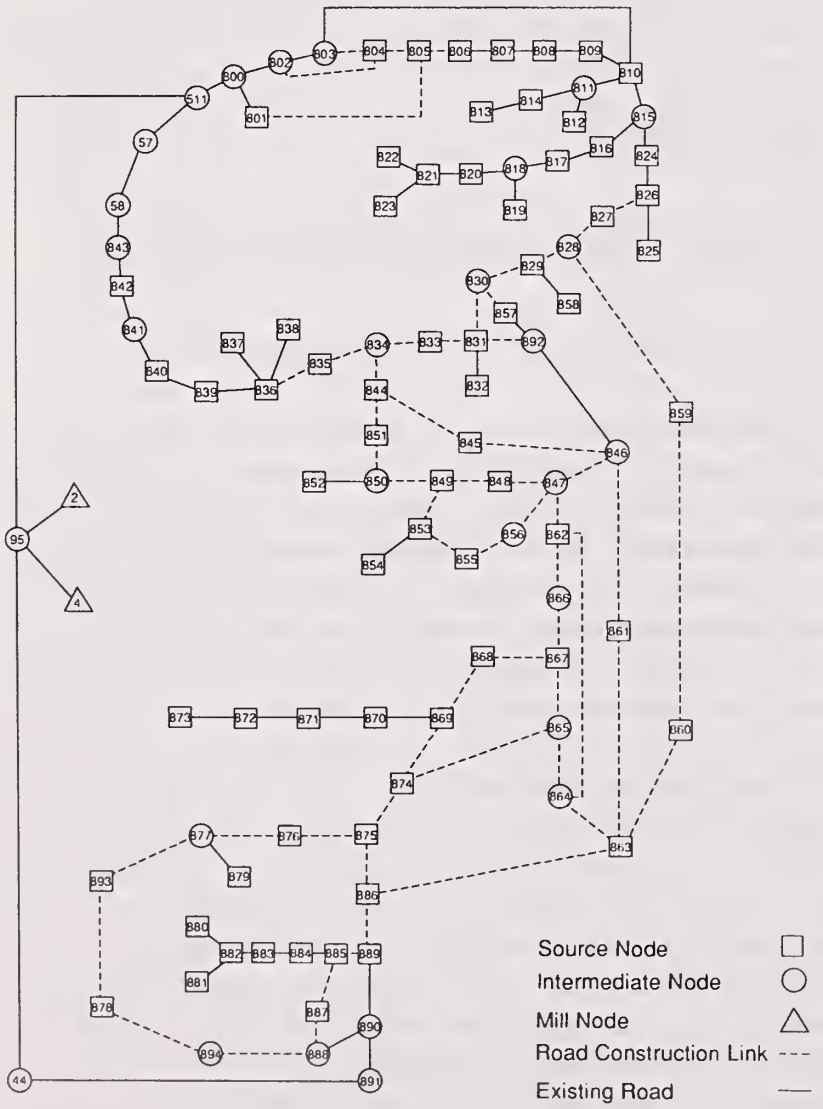


Figure 3--Network schematic for Silver Planning Area.

KOSCIUSKO PLANNING AREA
CODED NETWORK

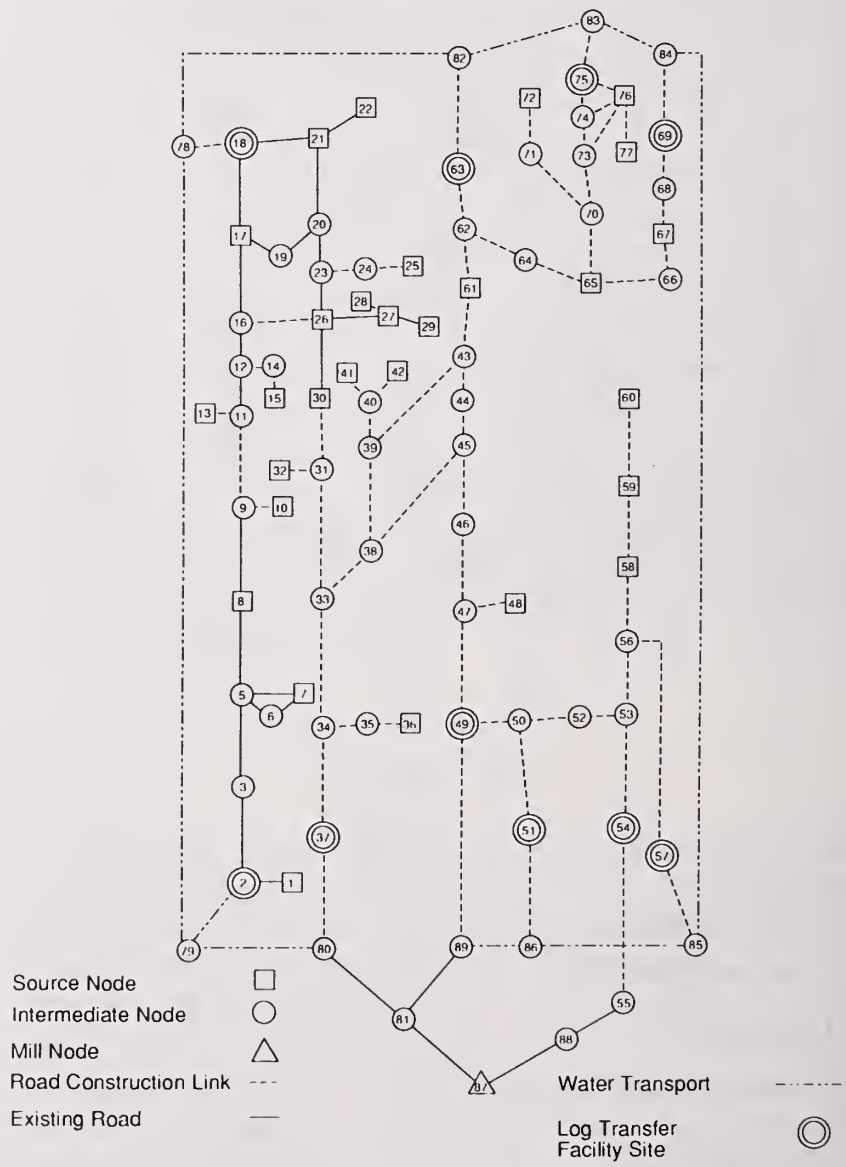


Figure 4--Network schematic for Kosciusko Planning Area.

Example Problem

The example shown in figure 6 is analyzed to demonstrate the analysis procedure. Assume there are five paths from one source node (timber sale) to a destination (mill). The solution with the lowest cost to this problem using the original data is $1,000 corresponding to path S-$1,000-M (fig. 6). One might ask, "Is this path truly the lowest cost or is there another path that has less cost when uncertainty in the data is considered?"

Five simulations are performed to illustrate the process. The original data are used as means to generate values of normally distributed variables. Five data sets are created representing five possibilities for the actual data that could be observed in the field at the time of implementation. The first simulation is described in detail. The random numbers used to arrive at the other four data sets (revised data) are not included.

Figure 6 shows the random normal numbers and data set for the first simulation. The lowest total network cost of the first simulation using the revised data is $1,067 which corresponds to path S-$1,200-M. The total cost for this network after substituting in the original data is $1,200. Table 2 summarizes the results of the five simulations.

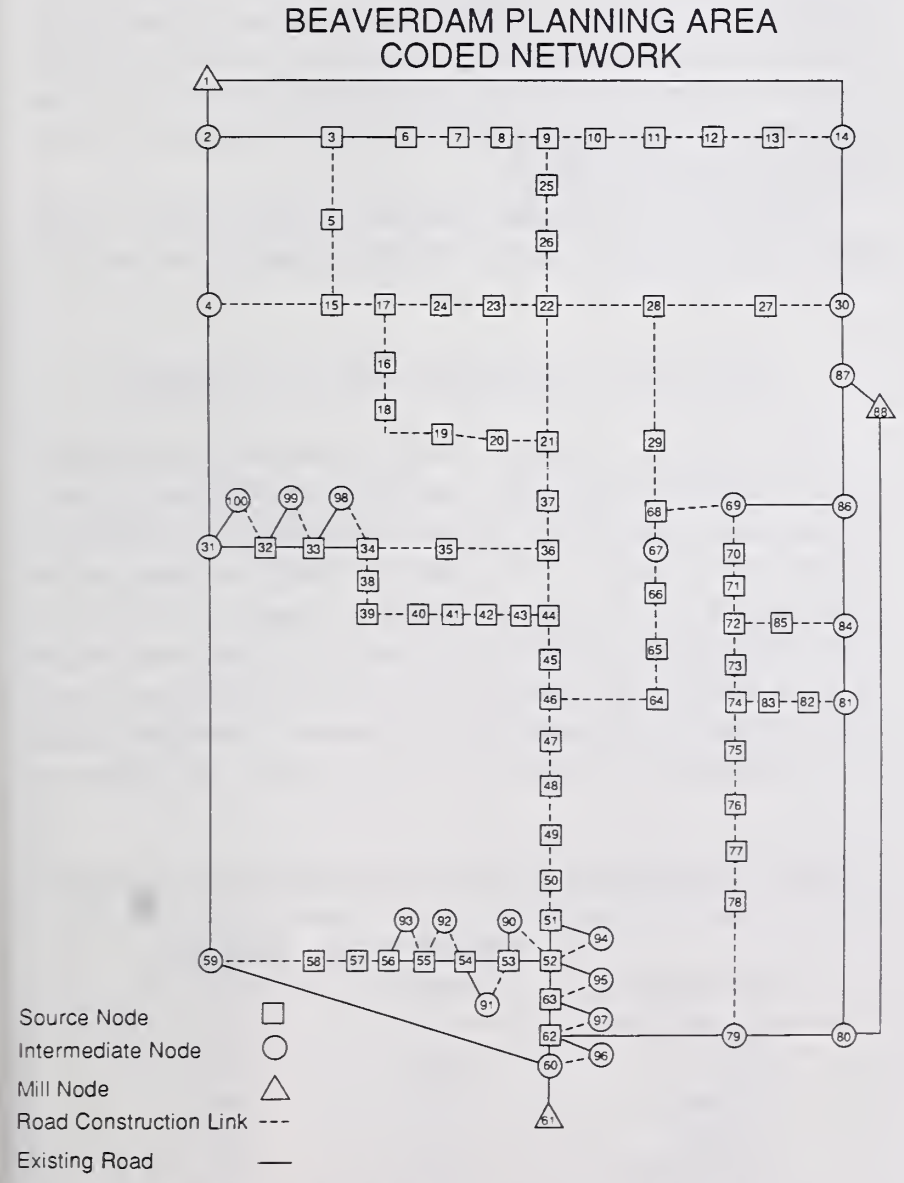


Figure 5--Network schematic for Beaverdam Planning Area.

Table 1.--Classification of networks from project areas.

Net. attributes	Off	Peavine	Silver	Kosciusko	Beaverdam
No. of sales	26	99	71	29	70
Total nodes	64	191	105	88	100
No. of arcs	169	338	170	153	213
No. of projects	22	55	58	69	84
No. of mills	3	1	2	1	3
No. of links	84	215	116	102	125
Sale volumes (mbf)					
Avg. (c)	3,281	528	1,330	9,900	207
S.D. (s)	3,436	756	700	10,970	285
Fixed costs					
Avg. (c)	218,300	18,400	61,900	305,850	5,090
S.D. (s)	257,800	43,300	35,800	462,739	3,740
Variable costs					
Avg. (c)	5.06	1.75	2.05	2.73	1.41
S.D. (s)	10.80	1.60	2.24	6.59	0.74
% of sale node in NETWORK	41%	52%	68%	33%	70%
% of links having fixed costs	26%	26%	50%	68%	67%
No. of 3-node loops	4	8	0	1	11

Table 2 shows that only one simulation chose the same solution path identified using the original data, i.e., path S-$1,000-M. Path S-$1,200-M was selected three times and path S-$1,100-M was selected once. The Stability Index value is:

$$\text{Stability Index} = \frac{1}{5} * 100 = 20\%$$

The Maxsim value for this example is:

$$\text{Maxsim} = \frac{3}{5} * 100 = 60\%$$

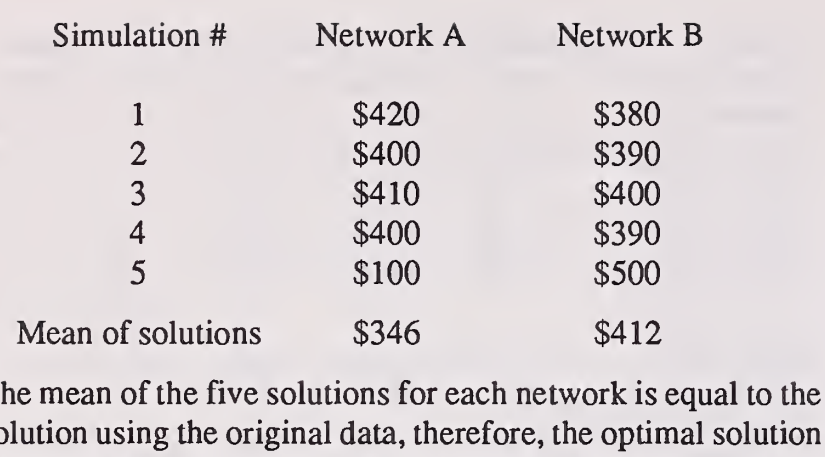
Since the Maxsim value is higher than the Stability Index value, the solution associated with the Maxsim value has a higher probability of being the optimal solution than the original solution set identified by the Stability Index. This does not mean however that this should be the solution selected for implementation. The paths associated with the Maxsim value, which have a higher probability of being the optimal when considering number of simulations run, will have a solution cost which is only slightly lower than the original solution. However, the paths associated with the Stability Index, although having a lower probability of being the optimal solution when evaluating strictly the number of occurrences, will be a much better solution when it is chosen.

The following example illustrates this point. Assume five simulations are run on a small network and all five results can be categorized as using the arcs in either Network A or Network B. The solution costs are:

Simulation #	Network A	Network B
1	$420	$380
2	$400	$390
3	$410	$400
4	$400	$390
5	$100	$500
Mean of solutions	$346	$412

The mean of the five solutions for each network is equal to the solution using the original data, therefore, the optimal solution identified by using the means of the data would be Network A. From the above example, Network A is superior to Network B for only one of the five simulations, i.e., Simulation Number 5. For the other four simulations, Network B has the lowest cost. The Stability Index value would be 20% and the Maxsim value would be 80%.

It would appear that Network B would be the better solution to implement; however, when Network A was better it was much better causing the mean of the solutions to be lower for Network A. For large organizations and agencies that can absorb moderate losses, adoption of Network A would provide the lowest expected cost. A small organization interested in minimizing the level of risk associated with an investment, might choose Network B even though it is not the lowest cost solution identified using the original data.



Simulation Data

Link	Random Normal Number		Std. Dev. **		Original Link Cost		Revised Cost
S-$1000-M	[+.805	x	$200]	+	$1000	=	$1160
S-$1100-M	[+.603	x	$220]	+	$1100	=	$1232
S-$1200-M	[-.551	x	$240]	+	$1200	=	$1067
S-$1300-M	[+.024	x	$260]	+	$1300	=	$1306
S-$1400-M	[+.125	x	$280]	+	$1400	=	$1435

NOTE: Lowest total cost = $1067 corresponding to path S-$1200-M.

** Standard Deviation = 0.2 x original link cost

Figure 6.--Network example showing costs associated with five paths from the sale node to the mill node and details of one simulation.

Table 2.--Summary of simulations.

Simulation #	Total cost with revised data (random variables)	Selected path	Total cost with original data (means)
1	$1,067	S-$1,200-M	$1,200
2	880	S-$1,000-M	$1,000
3	1,242	S-$1,200-M	$1,200
4	1,030	S-$1,100-M	$1,100
5	1,246	S-$1,200-M	$1,200

Application of Sensitivity Analysis to Study Areas

The approach described above was applied to the five field problems described earlier. A total of 100 simulations were made for each study area using the NETWORK model. The Stability Index and Maxsim values for each of the five areas are shown in table 3.

The Off Planning Area generated the highest Stability Index value of 76%. The Maxsim value for this area is also 76%. This network is relatively insensitive to the assumed variability in the input data.

Beaverdam and Silver Planning Areas are the most sensitive networks both having Stability Index values of one and a Maxsim value of two. Since both values are very small, further analysis is needed to determine which links in the network are used more than alternative links to attempt to narrow the focus of the subsequent analysis.

Peavine and Kosciusko both have Stability Index values close of 50%. These two are moderately sensitive networks.

Additional Implications of Sensitivity Analysis

Network sensitivity also provides an indication of the accuracy of the data needed. For example, the Off Planning Area, classed as an "insensitive" network, could tolerate a significant degree of variability in the input data and the same set of solution paths as the original solution set was selected 76 out of 100 simulations. Therefore, the data for this area need not be exact to identify the optimal solution. The collection of data used for this network need not be as intensive as with areas that are more sensitive. Peavine and Kosciusko, with moderate

Table 3.--Summary of stability index and maxsim values.

Planning area	Stability index value	Maxsim value
Off	76%	76%
Peavine	47%	47%
Silver	1%	2%
Kosciusko	48%	48%
Beaverdam	1%	2%

sensitivity values, would require more accurate data than Off Planning Area. Beaverdam and Silver, which are the most sensitive networks, require very accurate data for the analysis to be valid. It may not be possible to achieve this accuracy.

In addition to having uncertainty in the data, forest planning also involves resources for which some costs are intangible. Sensitivity analysis provides the probability of occurrence of alternative solution paths. This information can help the decision maker to weigh tangible and intangible costs. He might choose a solution with a higher expected cost if the probability of an outcome with a desirable intangible value is relatively higher.

Conclusions

Simulation can be used as a technique to evaluate the behavior of networks. Stability Index values that are high indicate relative insensitivity to variability in the original estimates. Values that are low identify sensitive networks and may require individual link analysis to determine the selected solution. Performing a sensitivity analysis on five field problems indicates that only the Off Planning Area is "insensitive" to the assumed variability in the input data.

The sensitivity of the network gives an indication of the accuracy of the data needed. Very sensitive areas require more accurate data than insensitive areas to provide meaningful results. Networks could be pretested to determine their sensitivity to establish data collection requirements.

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From Growth Models to Short-Term Timber Sale Scheduling: Design For a Flexible Link Serving Multiple Clients

P.J. Daugherty, J. Keith Gilless, Frieder Schurr, and Lawrence S. Davis[1]

Abstract.--The information forest managers need for short-term timber sale scheduling is a function of the owner's goals and constraints. A set of five computer programs, called the Stand Evaluator, provides a flexible link between timber sale scheduling programs and CACTOS and CRYPTOS (two California growth and yield simulators). The Stand Evaluator's programs post-process growth and yield data, averaging tree lists, simulating the bucking of trees into logs, valuing these logs, and producing a summary economic report. The user defines stand types and management units, and supplies bucking rules and economic data. Each program preserves intermediate results in a compact standardized data file. The flexibility of this link between growth and scheduling models results from preservation of intermediate data, a program structure that facilitates user modification, and reliance upon user-designed programs to meet specialized needs.

Stand or stand type growth and yield information requirements for short-term timber sale scheduling depend upon the owner's goals and constraints. Owners selling stumpage may be primarily concerned with total volume by species, and how this changes over time. Forest owners selling logs may be more interested in the distribution of volume by log size, and logging and hauling costs. Industrial owners with processing facilities may face constraints on species and log size distribution. Forest owners with multiple-use goals may have a wide variety of informational needs. For example, the canopy closure at different heights in a stand can serve as an index to bird habitat capability, and the distribution of stands by average diameter, basal area, and height may be useful for addressing visual resource requirements or wildlife concerns. To serve a diverse clientele, the design of a system for processing growth and yield data for forest management planning requires special attention to maintaining flexibility of access to the data and program functions.

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This paper discusses the design of a package of five computer programs, called the Stand Evaluator, that provide a flexible link between timber sale scheduling programs and the CACTOS and CRYPTOS programs. CACTOS, the CAlifornia Conifer Timber Output Simulator (Wensel et al., 1986), is a growth and yield model for young-growth mixed conifer stands in northern California. CRYPTOS, the Cooperative Redwood Yield Projects Timber Output Simulator (Wensel et al., 1987), is a similar model for the coastal redwood-Douglas fir region of California. Both are individual-tree, distance-independent models developed by the biometrics group at the University of California, Berkeley. The Stand Evaluator was developed under the auspices of the Economics/Management Project of the California Forest Research Association, an association of academic, industry, and governmental institutions.

Problem Definition

The cooperators funding this project included the University of California, the California Department of Forestry and

Fire Protection, five forest products companies, a private consulting company, and a public utility company. This group's diversity, along with the Land Grant mission of the University, provides a good example of the multiple client situation in which a broad range of goals and constraints are represented.

The diversity of goals and constraints was accompanied by diversity in informational processing capabilities and forest management decision models. Informational processing capability ranged from clients just beginning to use microcomputers to others operating integrated mainframe geographic information database management systems. Management decision models ranged from heuristic rule-based systems, in which stands are ranked by present net value, to sophisticated linear programming models with customized matrix generators. Figure 1 illustrates where the Stand Evaluator fits into the processing of growth and yield data in the context of clients with dissimilar information processing capabilities and decision models.

While the multiplicity of intended applications mandated a flexible design, our clients had common needs which anchored certain components of the Stand Evaluator. The basic unit of analysis for all clients was the stand or stand type. Both CACTOS and CRYPTOS are plot-based models. Hence the Evaluator had to be capable of aggregating plot-based data to the stand or stand type level. All clients had an interest in both short- and long-term timber sale scheduling. All wanted to be able to specify prices and cost estimates on volume by species and log size. The prevalence of multiple inventory plots per stand type required capacity for massive data throughput. In addition, all clients anticipated future increases in their information needs. Finally, all wanted built-in summary report writing capability for management units (or sets of stand types).

Design Criteria

Design criteria evolved from several meetings with our clients. These criteria fall into two overlapping categories dealing with program flexibility and common functional needs.

Flexibility Criteria

1. The system must allow use by clients with different goals and constraint sets.
2. The system must operate on micro, mini, or mainframe computers.
3. File handling conventions must allow for integration into geographic information data base management systems, while remaining usable by clients with less sophisticated data processing capabilities.
4. Output must allow for summarization at different levels of detail, and be suitable for forest management research.
5. The system needs to be easily modifiable to meet clients' specialized needs, and expandable to meet new information requirements.

Common Needs Criteria

1. The system must be capable of aggregating plot level growth data to the stand level.
2. The system must allow processing of either single plot or multi-plot data.

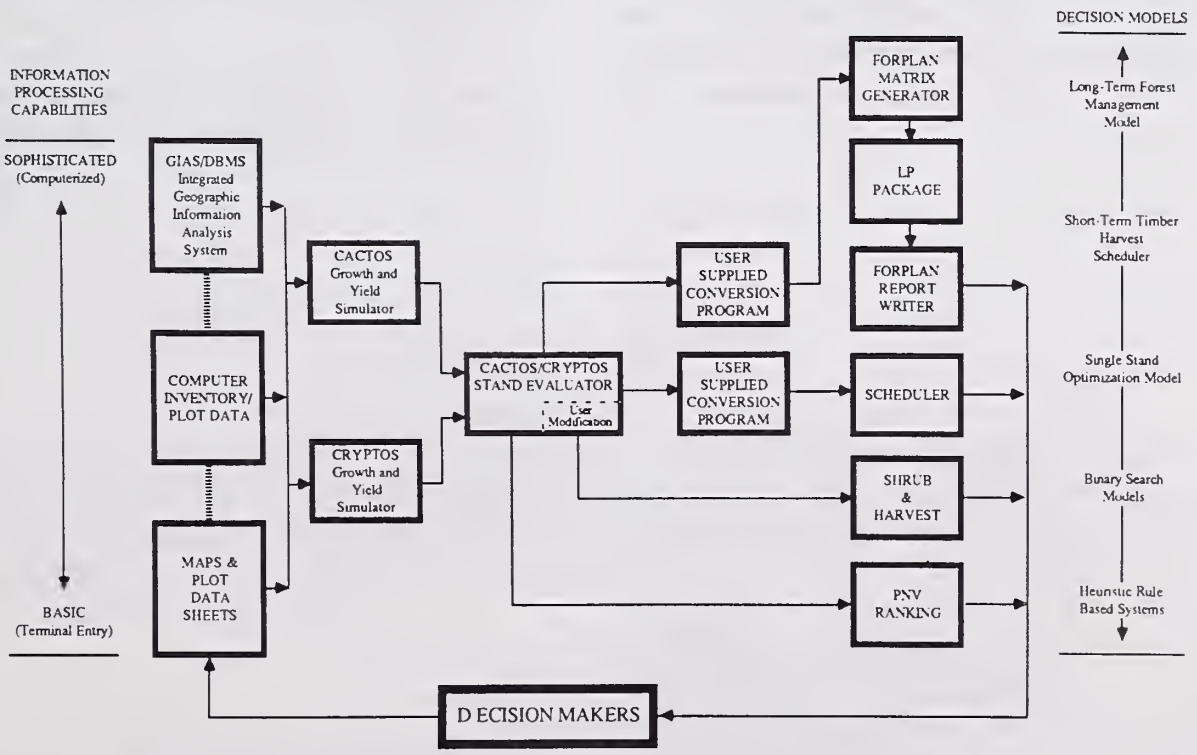


Figure 1.--Role of the Stand Evaluator in providing a flexible link between growth and yield models and short-term timber sale scheduling for diverse clients.

3. The stand level output data must be suitable for both short-term timber sale scheduling (i.e. annual growth and yield) and long term planning (i.e. periodic growth and yield).
4. The system must produce volume estimates, by species and log size, under a variety of bucking rules.
5. Valuation of volume must allow for consideration of price and cost schemes of different complexity.
6. The system must allow for the data throughput needed for detailed analysis of stands in decision making.
7. The system must have built-in summary report writing capability for user-defined management units.

System Design and Function

Overview

A modular system design for the Stand Evaluator (fig. 2) was developed to meet the above criteria. Each square box represents a single purpose program designed to perform a specific function. The Stand Evaluator programs are linked by compact standardized input/output data files which allow for multiple entry and exit points in the implementation of the system, and preservation of detailed intermediate results. The programs are minimally-interactive, batch-oriented processors suitable for linking by job control language. Each program has one or two control file(s) that allow for user specification of stand types, bucking rules, price and cost data, economic trend data, and management units. The FORTRAN code for each program was structured to facilitate user modification and addition of new functions and subprograms. The implementation of the system relies on user design programs to meet specialized needs.

System Components

CACTOS and CRYPTOS are capable of producing tree list files that represent the simulated development of a stand over time, allowing for intermediate harvests and ingrowth. These files contain a sequence of tree records and summary data describing the initial stand, and each growth cycle, harvest entry, and ingrowth addition. Five-year periodic growth equations are based upon plot level data, and predict the growth of individual tree records that describe the trees found on plots representing the stand type of interest.

The first Evaluator program, CTLAVG (the tree-list-averager) aggregates plot-based growth and yield data to the stand or stand type level. It produces an average tree list by calculating a weighted average of the plot-based tree lists produced by CACTOS/CRYPTOS. The program averages tree records by two inch diameter/twenty foot height class combinations, weighting by the number of trees/acre each record represents. This method preserves the variability represented by tree records, while reducing the total number of records processed by subsequent programs. The user defines stands or stand types by specifying the plot-based input files to be averaged. Optionally, differential weights can be assigned to input files. CTLAVG calculates a running average, effectively removing any program limitations on the number of plots to be averaged. This technique, coupled with the user assigned weights, allows the combination of new plot data and existing average tree list files.

YDSPLT (the yield-splitter) splits the periodic tree lists produced by CTLAVG into annual tree lists for use in short-term timber harvest scheduling. The user can request annual tree lists five or ten years in length. Standardization of input and output file formats allows users to bypass the CTLAVG program and route CACTOS/CRYPTOS output files directly to YDSPLT .

LGBUCK (the tree-to-log-bucker) converts tree list files into log list files that describe the growth and yield of merchantable timber over time. LGBUCK accepts CACTOS/CRYP-

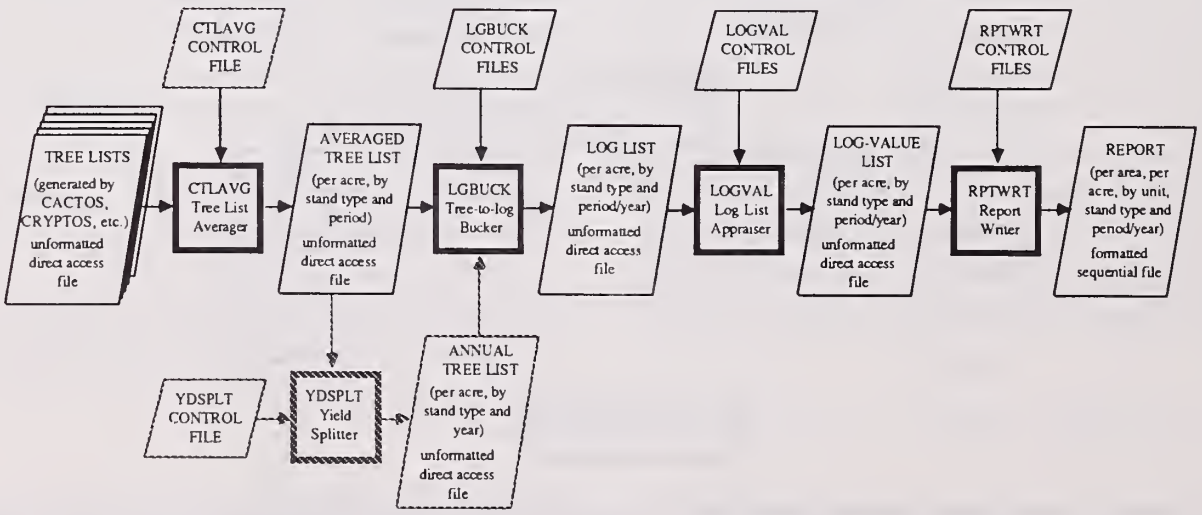


Figure 2.--Stand Evaluator program design.

TOS, CTLAVG, and YDSPLT output files. LGBUCK bucks tree records into log records on the basis of an user supplied control file. This file specifies general merchantability limits (i.e., min. DBH, min. top DIB, min. and max. log length, and scaling increment), preferred log lengths, and DIB limits for each length. These rules can be specified by species or species groups. Bucking rules are applied using taper equations to determine DIB at appropriate points on the tree, and the "bucked" logs are scaled according to Region 5 Scaling Bureau Standards. The program calculates both gross Scribner decimal C board foot and cubic foot volumes. Users have the option of specifying gross to net conversion factors to account for volume loss due to breakage, defect, and cull. LGBUCK writes out volume information by species, log length, and one inch top DIB classes.

LOGVAL (the log list appraiser) produces a log-value list file by associating user supplied prices and costs with individual log records. Prices and up to three types of costs (dollars per unit of volume) can be specified. The values of standing volume, intermediate harvests, and ingrowth are calculated in terms of the logs that would be produced if the corresponding trees were bucked as specified in the log list. The economic data input file is structured for compact specification of prices and costs. A size dependent price scheme for a species-grade group is specified by listing only the log lengths and DIBs where the unit prices change. Up to five log length breaks, and up to five DIB breaks per log length break, can be listed for each species-grade group. Costs schemes are specified in an analogous manner. Two cost types can be specified by log size, while the third can be specified by species and log size. The former are nominally identified as falling/bucking and skidding costs, and the latter as hauling cost. In practice, the three cost types can be used to account for any unit cost the user wishes to associate with a log. Prices and costs may be specified on either a per board foot or per cubic foot basis.

RPTWRT (the report writer) produces summary economic reports for user defined management units. The units are defined by specifying log-value list files and associated acreage that occurs in a unit. Trends in prices and costs over time can be specified in much the same format as the basic prices and costs. Trend schemes can be more or less complex than the price and costs scheme, to which they are applied. In addition, up to ten per area or per acre costs can be specified for the management unit or its component stand types. Costs can be further specified as applying to final harvest, intermediate harvest, or both. Users can also control reporting detail, which ranges from a management unit summary to detailed cash flow reports for individual stand types. Pseudo-management units of a single acre can be used to report economic data on a per acre basis.

Flexibility

The Stand Evaluator is composed of stand-alone programs dedicated to specific functions, linked by standardized data files. This design allows individual clients to use only the programs suited to their particular applications. Separation of functions at the program level allows for numerous natural entry/exit points in the system. Standardized data files allow for different paths through the first part of the system. A source language which conforms to an ANSI standard ensures the system's portability to micro, mini, and mainframe computers. The Stand Evaluator was written in STANDARD FORTRAN (ANSI X3.9 - 1977), commonly referred to as FORTRAN 77, for three reasons: (1) it is a widely accepted standard, (2) it is excellent at formula translation, and (3) it was the only language in which programming knowledge was readily available. The program source code follows structured programming conventions in order to facilitate user modifications.

The programs are designed as minimally-interactive, batch-oriented processors. Run-time input is limited to the names of the control file(s). This input is easily incorporated into job control language or batch files, allowing the programs to be run as a seamless batch system. The programs have no internal limit on the number of input files to be processed, so the quantity of data processed in a single run is only limited by disk storage capacity. This feature gives the system considerable throughput capability, subject to users' ability to design batch runs that fit within their hardware's limitations.

To ensure compatibility with geographic information, data base management systems, to combat file proliferation, and to facilitate batch processing, file conventions were developed for opening and naming files. When an error occurs opening an input file, an error message is written to a batch report file, corrective action is taken, and processing of next file or next set of files continues. Output file names are assumed to be "correct", and existing files with the same names are overwritten without warning. The Stand Evaluator's file naming conventions are designed to allow a user to know beforehand the names of all files that will be created in a run. In general, Stand Evaluator programs form output file names by concatenation of input file names, codes supplied in the control files, and mnemonic extensions. This file naming convention was added to the CACTOS and CRYPTOS growth models, allowing complete tracking of the process used to develop an output file. For example, a log list file with the name "S1RX2L3.LOG" could indicate that this file represents stand type one, managed under prescription two, and bucked according to rule three. File name formation in all programs is controlled by the same easily modified subprogram code.

A key feature of the Stand Evaluator's design is the preservation of intermediate results at each stage at the most detailed level practical, in a compact standardized file format. Preservation of detail allows for more rigorous model validation, and permits summarization in a form appropriate for a particular application. At the outset of the design process, the importance of preservation of detail was hammered home when the CACTOS/CRYPTOS output format had to be revised to preserve tree level data. All Stand Evaluator intermediate files are binary, fixed logical record length files that conform to IEEE standards for representation of data (e.g. 4-byte integer, 4-byte reals). This

file structure was selected for several reasons: (1) it is compact, containing only data (i.e., no end-of-record characters or blanks), (2) it allows for rapid unformatted access, (3) it preserves precision, (4) it is suitable for direct access rapid processing when partial information retrieval is desired, and (5) it can be read by programs written in any language that conforms to the IEEE standards for data representation. Data content is also standardized for all Stand Evaluator intermediate files. Each file has 100 records for header information, allowing the user (and the programs) to store information in dedicated locations. Header information stored in input files is consistently preserved in the associated output files. Following the header, files contain consecutive sets of summary and detailed data records for each growth period and stand entry. The summary indicates the type of entry and the number of records contained in the entry.

A final significant design feature of the Stand Evaluator is reliance on users to provide the final link to their particular decision making model. The system is complete only for those clients using heuristic scheduling systems such as "cut the stands with the highest present net value." Rather than attempting to provide output formats suitable for all decision making models, we identified common processing requirements and designed a system that would meet them, leaving the final data summarization and organization to user designed programs that would meet specialized needs.

Application/Evaluation

Final evaluation of the Stand Evaluator's design depends upon our client's ability to integrate the Evaluator into their own information processing and decision making systems. This section discusses applications in progress or completed since the Stand Evaluator's release to the clients at the beginning of 1988.

Figure 3 depicts an application of the Evaluator by a client using a heuristic sale scheduling model. This client is essentially using the Evaluator as an off-the-shelf system, processing plot data through CACTOS, CTLAVG, LGBUCK, LOGVAL, and RPTWRT in that sequence, and using the economic summary report to rank stand for harvesting according to present net value, total merchantable volume, and current growth rate. This particular client is moving towards more sophisticated analyses, but even their current implementation of the Evaluator represents a significant improvement over the stand type map/pickup truck method previously used.

Figure 4 represents an application currently under development by Professor Richard Barber (Humboldt State University) for the California Department of Forestry and Fire Protection. The application involves the use of the Stand Evaluator to provide a link between an inventory system, CRYPTOS, and a binary search model for short- and long-term management planning. The path taken through the Stand Evaluator uses all programs for the short-term model, but bypasses YDSPLT for the long-term model. RPTWRT's output writing subprogram is being modified to produce output suitable for input to the binary search model. This application is also using LGBUCK to develop gross-to-net volume conversion factors based on scale data.

Figure 5 represents the most sophisticated applications yet carried out by one of our clients. CTLAVG and LGBUCK were used in developing a two-stage, planning model on a mainframe computer for a timber company selling logs. A geographic information, data base management system was first used to develop average stand descriptions. These files were simulated in CACTOS under several management prescriptions, and then processed through LGBUCK. The LGBUCK program was modified to utilize taper equations developed by the client. A user designed program summarized yields by species and log size as a FORPLAN yield file for a district-level short-term timber sale scheduling model. Results from this model were used to retrieve multiple-plot stand descriptions by operating unit, for subsequent CACTOS simulation. The tree list were averaged by CTLAVG, processed by the modified LGBUCK program, and formatted into a FORPLAN yield file for an operating unit-level short-term harvest scheduling model.

At the University of California, we have developed an application using CACTOS, CTLAVG, YDSPLT, and LGBUCK to build a short-term, harvest scheduling demonstration model. FORPLAN is used for matrix generation. Yields are summarized by the DIB breaks that determine the path a log takes through a mill. The models run on a microcomputer, and illustrates the use of an alternative programming language (PASCAL) to process Stand Evaluator data files. We are also developing a microcomputer application that modifies Evaluator output for input into a spreadsheet-based sale scheduling system.

The variety of Stand Evaluator applications already developed is a direct result of Evaluator's design. Our clients have had no problems in carrying out the program modifications needed to suit their application. Since the file naming conventions have not been completely integrated into any client's system, judgment on their usefulness is premature.

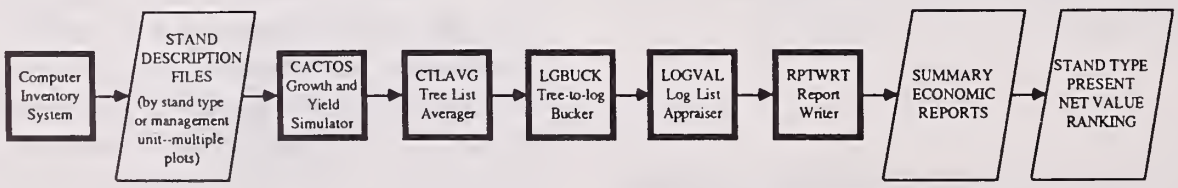


Figure 3.--Off-the-shelf application by a basic industrial user employing a heuristic forest management decision rule.

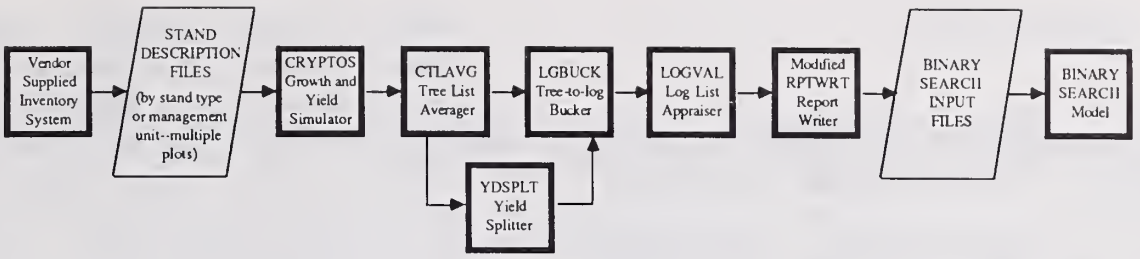


Figure 4.--Application under development by Richard Barber (Humboldt State University) for the California Department of Forestry and Fire Protection.

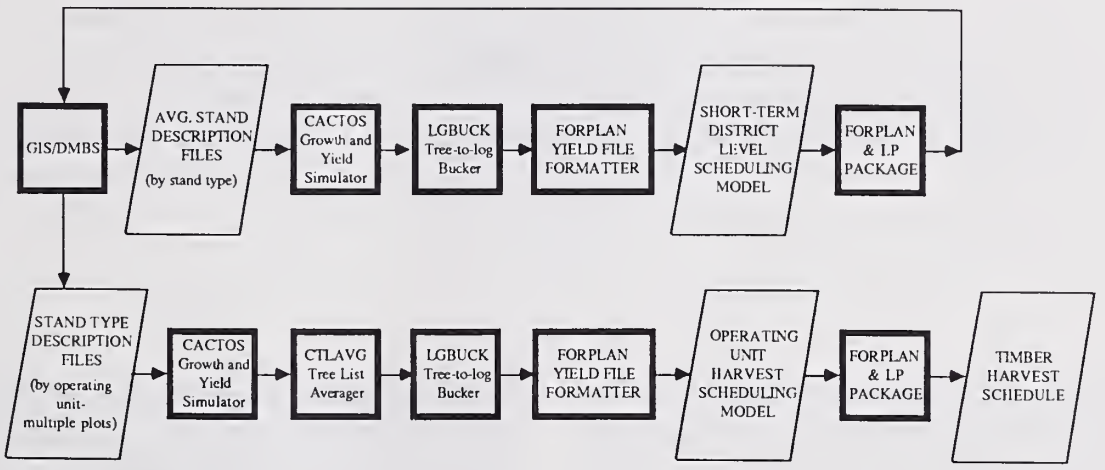


Figure 5.--Two-stage application developed by a sophisticated industrial client.

Several limitations on the implementation of the design criteria are known. Although structured programming conventions were followed, the time series character of CACTOS/CRYPTOS output files has made it difficult to add subprograms to the system for reading other sources of input data. One client found it easier to reformat their existing data on volume by log size and grade into our format than to develop a new LOGVAL input subprogram. Another limitation involves Evaluator data files. While these files conform to IEEE standards, the implementation of this standard varies between computer systems. As a result, intermediate data files are not directly transferable between systems. This problem was known early in the design process, and the decision was made that compactness and access speed was more important than intermediate data transfer between systems. A final limitation on the system is the system's steep learning curve. Our programming style has been nicknamed "user-hostile" because of the sophistication it assumes on the part of our clients. We make no apologies for this, since we consider flexibility and processing capability to be more important, and because of the steady growth in sophistication of the nonacademic forestry community.

Conclusions

The design process and final design of the Stand Evaluator raises some interesting issues in linking growth models and timber sale scheduling models for multiple clients. We have concluded that the system should be modular in design, allowing clients to use only those programs they need. Individual programs should focus on single, commonly needed functions, while the development of specialized applications should be left to individual clients. A standardized data file should be employed that preserves the intermediate results at a detailed level, to allow for validation and summarization at a later point. File handling conventions need to be flexible, yet standardized to allow for incorporation into existing systems. Programs should be written in a standard language to allow portability. Finally, coding should follow structured programming conventions to facilitate modification by clients.

The Stand Evaluator represents an attempt to meet these criteria and offers some questions that have yet to be resolved by forest system analysts. The requirement for standardized output raises the question whether as systems analysts we can agree upon standards to ensure compatibility of independently developed systems. The skill requirements to produce well structured program code raises the question as to whether nonprofessional programmers (i.e., most of us) should be writing code at all, or just designing the systems and hiring "real" programmers to generate the code. Finally, the release of source code to the clients, an inherent requirement of the Stand Evaluator's design, raises a number of touchy questions, regarding authorship credit, secondary distribution of the code, and compensation that need to be addressed by the forestry community's system analysts, academic and governmental research organizations, and forest industries.

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A Dynamic Programming Model for *Pinus hartwegii* in Central Mexico

Juan M. Torres-Rojo and J. Douglas Brodie[1]

Abstract.--A Dynamic Programming algorithm was incorporated to a growth and yield model to compute optimal thinning schedules. The algorithm optimizes timing, intensity, and type of thinning at different rotation ages.

A whole stand growth and yield model for *Pinus hartwegii* Lindl. was developed. Prediction equations are based on the compatible growth and yield prediction principle. Unit area yield estimates in the model are based on only four variables: basal area, number of trees per hectare, age, and site quality. A set of equations to describe the diameter distributions was adapted to the model. This set of equations predicts the parameters of a Weibull probability density function. By integrating the function over the desired class interval the frequencies for each class are estimated. Through this feature, the model is capable of predicting growth and yield after different intensities and thinning types are simulated.

The growth and yield model was then used as the basic production surface in a standard Dynamic Programming formulation to optimize thinning intensity, timing, type of thinning, and determine optimal rotation ages based on both soil expectation value and present net worth.

The optimizer consists of a Network whose nodes define different stand conditions at different periods. The optimization problem is defined as the maximization of the present net worth or soil expectation value over the rotation. The problem is formulated as a discrete time, discrete state Dynamic Programming problem. Forward recreation is used to identify the optimal treatment schedule.

The formulation does not require additional state variables to account for the thinning type optimization. It allows three thinning types, from below, from above and mechanical thinning.

The model can accept different pricing strategies for the harvested trees, i.e., it identifies different quality premiums. Thus the effect of having different monopsonistic buyers can be evaluated.

[1]*Graduate student on leave from the National Institute of Forest Research, Mexico, and Professor, Department of Forest Management, College of Forestry, Oregon State University.*

Queuing Simulation of Skidding Using XCELL+

Rakesh Gupta and Joseph P. Roise[1]

Abstract.--This paper describes an attempt to use XCELL+, a factory modeling software package, to simulate the use of skidder harvesting operations. XCELL+ is used to build a "logical model" of the production facility on a personal computer and to "run" that model to measure capacity and other production characteristics. Unlike the typical production system where the work center is static, the work center in this situation is dynamic.

The production of solid lumber, paper, and composite wood products is preceded by timber harvesting, the raw material delivery component of a wood production system. Steps involved in processing and movement of wood from stump to mill resembles those of other raw material extraction processes. Problems associated with production planning are similar for most raw material extraction operations. Raw material extraction is often characterized by relatively simple processing steps but complex material handling requirements. Extraction systems can be viewed as part of a factory, but with the dimensions of the factory changing with each new site. Managers and production planners must consider the variability introduced by changes in raw material characteristics, the general terrain of the area and the equipment available to move and process the raw material.

Machines used for harvesting wood are expensive, and thus, should be chosen for efficiency over a wide range of stand conditions. Fully mechanized logging has accomplished a considerable reduction in harvesting costs. This does not mean we should not strive for more efficient harvesting methods.

The traditional method used to select an optimal machine configuration has been the assembly line balancing method. Though an easy to use technique, it does not take into account interference between machines in the system. Queuing simulation, logical alternative, accounts for random interference. This paper emphasizes the interaction between machines in a system, as well as the production and utilization of individual machines. This analysis method provides the user the option to test alternative strategies for raw material extraction and to get an inexpensive understanding of a systems performance.

A queuing model approach which studies harvesting operation by simulation appears to be promising (Webster 1975). Simulation is a promising method for analyzing harvesting operations because timber harvesting systems have so many random variables as to defy systems analysis by any other method. Other techniques will not allow an analyst to take into account anywhere near the number of significant variables nor encompass the entire harvesting operation.

A simulation model is a mathematical model which imitates a real life process. This paper will describe a simple simulation model which enables us to study machine combinations for harvesting without recourse to expensive field trial. The discussion in this paper is directed toward an analysis of the major types of ground skidding timber harvesting operations used in southern bottomland hardwood sites.

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MODEL OBJECTIVES

To use XCELL+, a factory modeling system, to simulate a typical forest harvesting operation. The specific objective are:

a. To develop a "logical model" of the operation on a personal computer.
b. To estimate production capacity, cost, and system bottlenecks.
c. To compare different machine systems and single out the best one.

XCELL+

XCELL+ is a computer application package that enables the construction of "logical models" of any production process. Simulation of production processes has been used with considerable success for many years. Without XCELL+, use of

simulation requires expertise in a specialized programming language. As a result, simulation was generally practiced by technical specialists, rather than by engineers and managers who are actually faced with the problem. Packages like XCELL+ represent a "spreadsheet approach" to simulation. XCELL+ can best be characterized as a "menu-driven system." That means that at each point in its use the possible actions are presented as a menu of choices. XCELL+ runs on personal computers, which adds to its appeal.

XCELL+ describes a factory floor as a uniform rectangular grid. Its intent is to represent only the logical relationship between elements, and it uses geometric representation only as a tool. The basic XCELL+ building block, are:

1. Workcenters--where Processes are run and work is performed.
2. Receiving areas--where material is received from the outside.
3. Buffers--where work-in-progress inventory is stored.
4. Shipping areas--from which finished material is shipped to the outside world.
5. Maintenance facility--where service teams are sent from to repair or provide scheduled maintenance for Workcenters.
6. Auxiliary resource--site from which resources are supplied to perform processes.
7. Control points--intersection of paths, and traffic control points in an asynchronous materials handling system.
8. Segment--of a path, connecting two control points, over which carriers can transport material.

In addition to these eight different types of elements, there are three other important design features:

1. Processes describes the work done at a workcenter. A particular workcenter can have many processes but only one can be active at a time.
2. Links describes the material flow to and from a process or a control point. A link can be regarded as an infinitely fast conveyor with no storage capacity.
3. Carriers are moving elements, superimposed on segments or control points, to carry loads over a materials handling network.

DATA COLLECTION AND ANALYSIS

The study was conducted on a site bordering the Pascagoula River in George County, Mississippi, owned by Scott Paper Company. The site was hand felled 1 week ahead of skidding. Three skidding systems with hauling distances of 0-1,500 feet were identified. Large and small rubber tired skidders were the CAT518 and CAT508. A crawler type skidder was a custom CATD5H. A brief description of the skidders follows.

CAT508 Grapple Skidder

The 508 is one of the caterpillars low power grapple skidders. It has a power rating of 95hp/75kw as compared to 130hp/97kw of CAT518. This skidder was fitted with a 28-inch rubber tire and a 82-inch grapple and shear. This skidder falls in the category of small skidder.

CAT518 Grapple Skidder

The horse power of this skidder is 130hp/97kw and falls in the category of large skidder. It was fitted with a 34-inch tire and a 100-inch grapple.

CATD5H Custom Grapple Skidder

This is considered to be a large track skidder. The horse power rating of this skidder is 120hp/89.5kw.

For the execution of the experiment, a three member data gathering crew was assigned to each machine system. The person in the woods recorded the start and end of the bunching process. The people at the landing were recording arrival, departure, and load characteristics. The species and number of trees per cycle were recorded by plot (skidding distance range) to measure production rate. Each log's length and diameter were recorded and the volume calculated using taper function tables (2). The skidders were harvesting tree length logs.

The plot was divided into four subplots with skidding distance ranges of 0-400 feet, 400-700 feet, 700-1,100 feet, and 1,100-1,500 feet. Following parameters were recorded to measure productivity.

Load Size

The load was measured in terms of three parameters:

a. Trees and Type (pine or hardwood)--each tree was numbered to measure skidder cycle and for truck load.
b. Tree length.
c. Tree diameter.

Time

A typical cycle consists of following elements:

a. Bunching time--starts the instant when the skidder picks up the first tree and ends with the instant the skidder picks the last.

Table 1.--Summary of time and motion study using three skidding systems.

Skidding distance	508		518		D5H	
(feet)	Mean	S.D.	Mean	S.D.	Mean	S.D.
			Cycle time (seconds)			
0-400	238.04	118.18	262.94	103.60	324.35	120.09
400-700	363.30	124.08	487.71	171.44	497.85	136.18
700-1,100	504.09	135.41	515.57	142.92	608.80	118.23
1,100-1,500	704.19	280.51	705.43	145.37	759.70	101.65
			Bunching time (seconds)			
0-400	80.18	53.72	91.57	56.89	152.37	97.66
400-700	118.32	62.93	198.44	141.87	249.13	120.47
700-1,100	162.00	98.50	209.15	109.45	240.25	123.74
1,100-1,500	186.19	141.94	280.00	124.44	242.80	107.13
			Travel loaded (seconds)			
1-400	86.76	62.49	85.03	50.48	75.21	49.3
400-700	163.19	97.35	205.39	59.11	107.00	30.06
700-1,100	165.78	63.98	199.58	42.23	173.84	53.66
1,100-1,500	236.41	80.17	247.64	66.47	245.04	43.89
			Travel unloaded (seconds)			
0-400	82.86	47.49	83.75	61.50	100.46	44.06
400-700	85.06	59.97	73.41	63.58	147.43	36.59
700-1,100	185.43	90.55	102.77	51.45	194.70	48.67
1,100-1,500	271.47	198.15	183.57	94.55	252.57	35.80

b. Travel loaded--starts when bunching ends and ends when the skidder drops the load at landing.

c. Travel unloaded--the time consumed by the skidder to travel from landing to the bunching site.

d. Downtime--accounts for any loss in time other than the normal course of activity. According to the Silviculture Equipment Handbook of the Government of Canada, the downtime can be of various types. A few of them were defined as:

   1. Active repair--repair constitute the mending or replacement of the part that has failed or has malfunctioned.

   2. Service--regular maintenance that a machine requires for its satisfactory operation.

3. Delay--time when the machine is not performing its primary function for reasons other than active repair and service.

DATA ANALYSIS

The data was analyzed using SAS, a statistical software package. Volume was calculated from large end diameter and height of the tree. Max and Burkhart's taper and volume functions were used (Martin 1981). Max and Burkhart's approach is to develop three separate submodels that describe the bole. The version selected for our study was their quadratic-quadratic-quadratic model.

Using SAS/BASE and SAS/STAT software, mean, standard deviation, and probability distribution were evaluated (SAS 1988). Tables 1 and 2 detail the elemental times and volume on a sub-plot basis for three different machine systems.

MODEL DEVELOPMENT

In a normal production system the work centers are static. This in not the case in harvesting. In harvesting the work center, skidder is dynamic. It moves from one location to another. To

Table 2.--Summary of time and volume data used in the model.

Skidding distance *(feet)*	Avg. processing time *(seconds)*	Average setup time *(seconds)*	Volume harvested *(cubic feet)*
CAT508			
0-400	3.36	1.70	3,990
400-700	5.19	1.30	3,542
700-1,100	5.03	2.75	3,953
1,100-1,500	6.53	4.33	4,738
CAT518			
0-400	2.68	1.39	2,797
400-700	6.30	1.11	1,296
700-1,100	5.26	1.41	2,987
1,100-1,500	5.75	1.93	2,218
CATD5H			
0-400	1.53	4.04	1,651
400-700	5.26	2.23	2,261
700-1,100	4.30	2.00	3,649
1,100-1,500	5.86	2.63	3,931

cope with this situation, we conceptualized the system as if the logs were dynamic and were flowing into the work center. So skidders were left static. This conceptualization allowed us to use XCELL+ modeling system.

Processing time at the work center is equal to the sum of travel loaded and bunching time. Setup time of skidder is equal to the travel unloaded part of cycle time. Using SAS programs, probability distribution and mean of these times for each machine is calculated. Table 3 details these times for each machine system. Both the processing and setup time are measured on a per unit volume of wood harvested.

The four subplots (0-400 feet, 400-700 feet, 700-1,100 feet, 1,100-1,500 feet) were simulated as receiving area. The inventory size for each receiving area was made equal to the volume harvested from that plot in the real experiment. Since the processing time and setup time increases as the skidding distance increases, the same skidder was modeled as four work centers each having different processing time and setup time. The landing is modeled as a buffer having finite capacity. The loader is simulated as another work center having a definite processing and setup time. Finally, the factory where logs are ultimately shipped is represented as a shipping area. The shipping area has unlimited capacity.

The flow of logs and the structural diagram is shown in figure 1. Logs flow from their respective receiving area into workcenters and then into the buffer (landing). When the landing reaches its capacity, the loader starts putting the logs on a truck or a forwarder, which carries them to the shipping area (factory). On work centers 2, 3, and 4, a lower trigger is implemented (i.e., work center 2 is triggered only when all logs have been removed from receiving area R1). All work centers operate sequentially in the order of WC1, followed by WC2, followed by WC3, and lastly WC4. The loader has a high trigger on it, which means it is active only when buffer (landing) reaches its capacity.

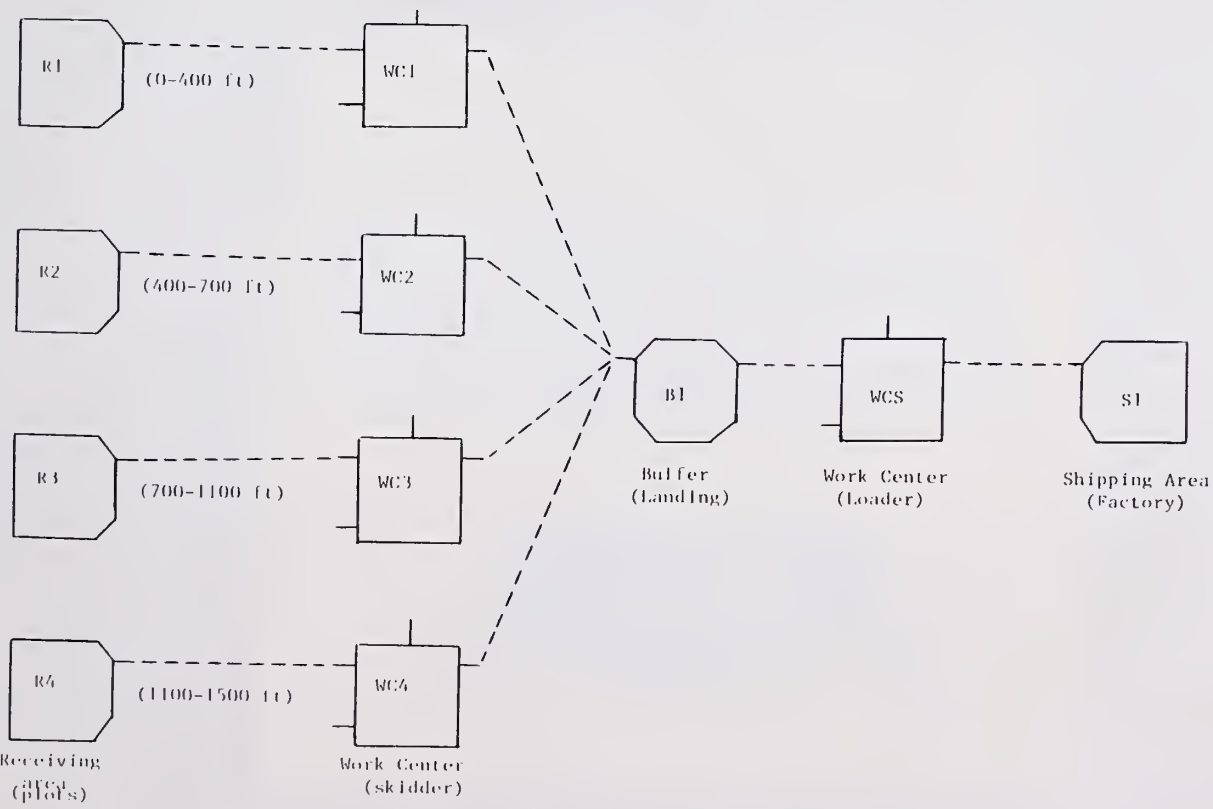


Figure 1.--Structural diagram of the model.

Table 3.--Summary of simulation results. Simulation was run until all volume was harvested.

Machine system	Throughput *(cubic feet)*	Cost unit/time	Work center utilization
CAT508	16,223	0.236	1.955
CAT518	9,298	0.132	1.048
CATD5H	11,492	0.165	1.356

RESULTS

Refer to table 3 for summary of simulation results. It can be seen that CAT518 comes out first with minimum cost/time. The work center utilization of CAT518 is minimum, followed by CATD5H and CAT508, respectively.

CONCLUSION

It can be concluded that use of XCELL+ is convenient and fast. Its use does not require any advance expertise in any particular programming language. This makes the tool particularly useful for managers and engineers to evaluate alternative strategies. The conceptual model of the production system is visible. There is no abstractness in the model, which is the case with most simulation languages. XCELL+ being menu driven is very easy to use.

Scope for Future Work

Future work will be in the following areas:

a. Modeling the trucking and forwarding operation.

b. Modeling that mixed species (like pine and hardwood) are harvested together but shipped separately.

c. Modeling the sorting of logs into saw logs and pulpwood either at the landing.

d.Inducing maintenance and associated downtime into the model.

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These proceedings contain the papers of the third symposium on systems analysis in forest resources management, held at Asilomar Conference Center, in Pacific Grove, Calif., in the spring of 1988. As with two previous meetings, a diverse and interesting group of papers was presented. General topic areas include land management planning, artificial intelligence, multicriteria optimization and fuzzy systems, regional timber supply analyses, stand level optimizations, and timber harvest scheduling.

Keywords: Land management planning, systems analysis, forest management, modeling, natural resource economics.

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